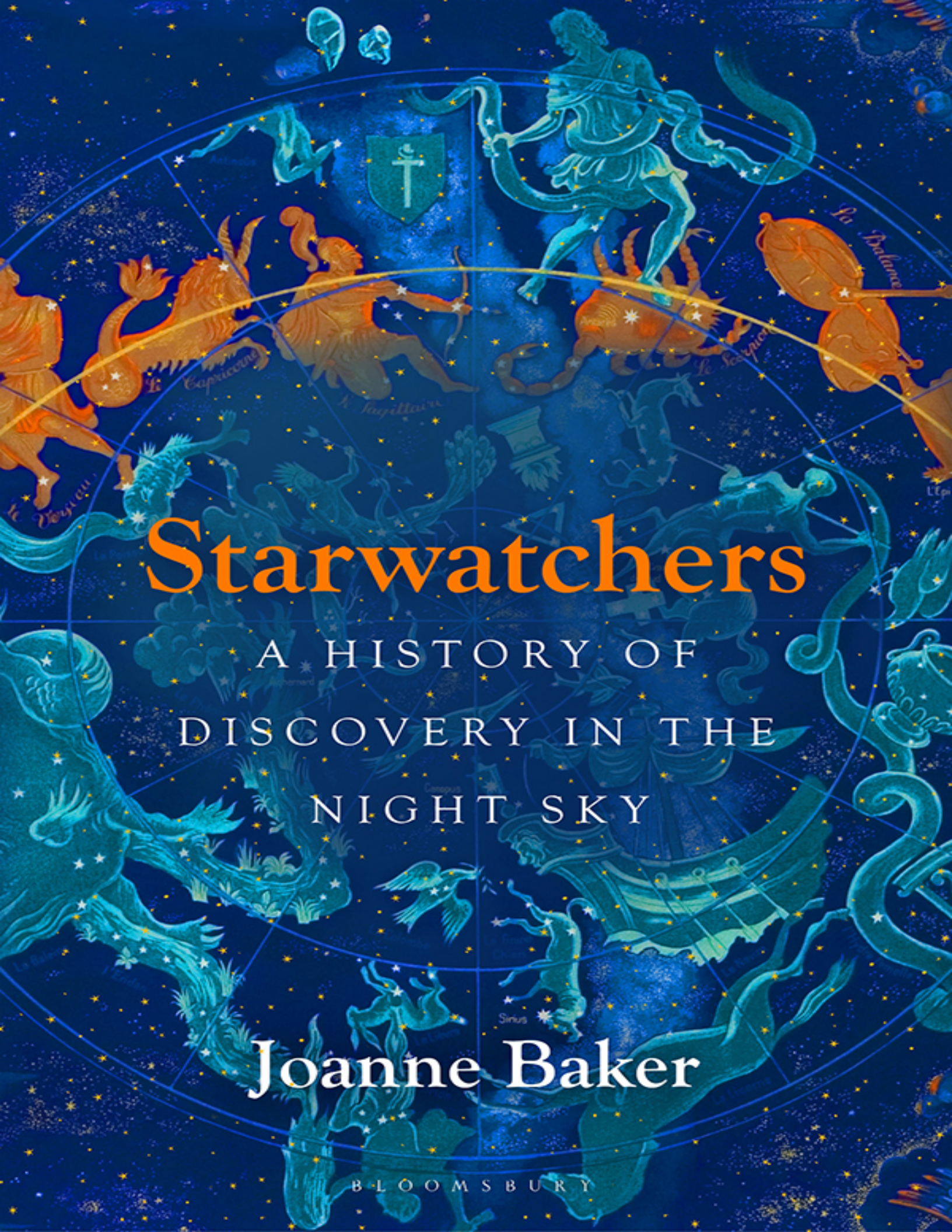




Starwatchers

A HISTORY OF
DISCOVERY IN THE
NIGHT SKY

Joanne Baker

BLOOMSBURY

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Introduction

Our Drive to Know Space

One question has driven the arc of my life: what draws us to the heavens and how can we as humans make sense of all that lies there?

I became fascinated with the stars and planets as a child growing up in a sturdy grey-granite house on a windswept clifftop on the western tip of Cornwall in the 1970s. Walls two feet thick stopped the slew of winter storms from blowing us into the valley, although we had to dodge the occasional falling slate and bags of shopping blasted from the car across the gorse. From my parents' bedroom window, at the end of the day, I would watch the Sun slip silently into the Atlantic, hoping to spot the elusive 'green flash' (I never did). I'd look on in awe as first one, then a dozen, then tens, then hundreds of pinpricks of light gradually emerged from the gloaming.

I got to know the soft red tint of Mars and the confident glare of Jupiter, and traced their paths across the sky through the year. I started to pore over coffee-table atlases of astronomy, heavy with star charts and alluring photographs of nebulae in space looking like glowing splatters of candy floss and clusters of stars glinting like clutches of sapphires, emeralds and rubies.

As winter storms howled outside and then abated, plucky daffodils and sea thrifts popping up their heads to meet the Sun's warmth in spring, I wondered about wildernesses and forces of nature beyond our planet. It was not many years since NASA's Apollo Moon landings – television still showed grainy black-and-white pictures of proud American men in padded white suits bouncing over a desert of grey dust or careening like clowns over rocks in their rovers. Reflections in their visors hinted at mountains and craters beyond, lit by blinding white light.

At junior school, while painting orange stripes and a red oval on a pencil sketch of Jupiter or trying to work out how to draw Saturn's rings so they didn't look like ears, I wondered about the nature of those planets. I don't recall questioning then why they existed – Mars and Venus, Jupiter and Saturn just were, like my mum and dad and sister, cats, dolphins and gulls, cars, tap water and electricity. But something about them took hold in my mind.

In 1976, just as colour television spread across the UK, NASA's Viking landers revealed the surface of Mars. The robotic probes beamed back pictures of a barren plain littered with rust-red rocks set against a pale apricot sky. It looked more like a film set for *Star Trek* or *Doctor Who* than an alien world. The oddly recognisable landscape seemed to beg for people to go there. How different from a desert on Earth could it be? And how exciting to go and see it in person, to experience Mars's sense of place! It became another destination for explorers. Mount Everest was conquered, and the Moon. What next – Mars? It seemed so obvious.

The following year saw the launches of the planet-hopping Voyager 1 and 2 space probes, whose postcards from their grand tour of the solar system I eagerly awaited every

couple of years. As I grew in height, I notched off their destinations. First Jupiter, with its fuming stripes and ominous 'red spot', a vast cyclone as mesmerising as a cyclops's eye. Next Saturn's majestic rings, vast circles formed from myriad blocks of ice, interrupted by sharp gaps like grooves on a vinyl record.

My horizons expanded with those of the far-flung probes. My 17th birthday coincided with the first flyby of Uranus. It turned out to be a disappointingly bland grey-green sphere. A year later, Neptune was revealed as a slightly more pleasing blue marble streaked with white clouds. There was a lot that was strangely familiar, even at the solar system's outer edge.

Hoping to learn more about these stars and planets and how the Universe works, I studied physics at university. There I found out a lot about the mechanics of the cosmos: heat and energy, fundamental forces such as electromagnetism and gravity, and the constituents of matter, from electrons to quarks. But, apart from a brief taste of astronomy in my final year, the lecturers said little about the origins of these celestial bodies, or about the long history of people trying to understand our place in the cosmos. We students had to accept that the physical description was the only tale. Cosmology, and much of physics, was an intellectual and mathematical pursuit, nothing more.

That left me hungry. Obviously, there was more to it than could be taught in an undergraduate degree. And so I studied more. I pursued a PhD in astrophysics, travelling to the other side of the world to Sydney, Australia, to get a broader perspective. I wanted to know what the forces were that made the Universe tick. What else was out there? Why are we here?

As a graduate student, and afterwards, I studied quasars, the glowing clouds of material around giant black holes that emit immense amounts of radiation into the Universe. I worked on getting to know around one hundred quasars well – a sample of distant galaxies centred around internal fires driven by black holes burning in their bellies. I was the first person to examine these particular quasars in such detail, and I still feel strangely attached to them: I was part of their lives for a decade as they are part of mine.

None had a familiar name, just a number, based on their position in the sky. But, to me, each had a character – from being inscrutably bright and brash to soft and smouldering. Some had arcs of gas pulled out like veils around them. Others hid in clusters of smaller galaxies. Some were smothered in dense clouds that hid their light and contained them. Some pointed their faces straight at me; others were shyer and only shared their profiles side-on.

I kept studying them, and other aspects of the distant Universe, for a decade, while based in the UK and US. I feel privileged to have used some of the world's finest telescopes, in exotic and remote places from Hawaii to the Chilean Andes and the Atacama Desert. I still pinch myself to think I once controlled the Hubble Space Telescope, writing instructions telling it where to point and click as it whizzed forty times around the Earth.

Yet even after more than a decade of searching, I had more questions than answers. Astrophysics was revealing amazing things, and it was incredible that I could find new patterns in the cosmos. But the story was still being told in dry symbols and jargon, the astrophysical Universe increasingly a place of abstract mathematics. Competing for grants and kudos seemed more important than the pure joy all astronomers feel when working at a telescope. You could

be the first or only person to ever get to know a star, a quasar or a canyon on a planet away from Earth, receiving light that had taken as long as billions of years to reach you. But that seemed apart from our everyday lives. Looking back to Earth and humanity, things seemed safer, more tangible and more urgent. I stepped back from active research and enrolled as an editor on scientific journals to keep my curiosity fed.

As a former astronomer, I've seen how aspects of space are objectified and quantified. Yes, scientists love what they work on, and many, like me, were drawn to their field by a sense of awe and a desire to make discoveries and breakthroughs, to understand how nature works. But in reality, most scientists spend their time treating extraterrestrial places as things to be measured and sized up.

For what? Sometimes they are seen as potential reservoirs of fresh resources, to be tapped once we've consumed all the easy-to-reach minerals on Earth, to make rich men richer. Or as places to change – to 'terraform' to be more like the Earth we're failing to manage. At best, they are seen as primordial places that can tell us more about our own importance – our origins and that of earthly life.

Equating the night sky only with physics and maths and money makes it seem expendable and distant. But there are millennia of human history up there too. We are in the stars. Stories we have told to and about ourselves are spelled out in constellations. Our sense of what it means to be human has changed as we have learned more about the Universe. Knowing the stars and planets do not revolve around us forces humans to be humble: a sideshow, not the main act.

As the curtains of the cosmos have been pulled back, as we delve ever further, humanity has conjured up new tales

to explain what we see. Most of us don't know quite what we are looking at when we see an image of a gas nebula in rainbow colours - often highlighting different gases giving off different hues of light. But we know it is beautiful. We give these celestial clouds familiar names - the Crab Nebula, the Antennae Galaxies, the Sombrero Galaxy. And the more we see, the more familiar we get, the more we want to go there.

The range of exploration, both human and robotic, is expanding fast. It's been more than fifty years since humans walked on the Moon, and although we haven't been further in person (yet), the planet Mars has been mapped and photographed down to an inch. Its red landscapes can be almost as familiar to us as those of the Australian interior or the Atacama Desert. Even though we may have never been to either, a visit to Mars seems just as plausible.

Since the 1960s, space has been deemed 'a province of all mankind', a global (or, indeed, extra-global) commons. In theory, anyone has rights to go there and sample its fruits. When the Outer Space Treaty that codified this was agreed in 1967, the Soviets and Americans could afford to be generous: only they had powerful enough rockets to reach space. Now that balance is changing, as Europe, China and India are joining in. Commercial companies and billionaires are getting in on the act too, like Elon Musk's SpaceX and Richard Branson's Virgin Galactic. To entrepreneurs like them, space is a new frontier brimming with natural resources waiting to be bagged. Like the American 'Wild West', it risks being fenced off, risks ceasing to be wild.

There are many reasons for this new space race. Geopolitics is one. The launch of Sputnik, the first orbiting satellite, by the Soviets in 1957 scared the United States enough to provoke the moonshots. The world stayed up to

watch Neil Armstrong's first step onto the lunar surface – one of the great shared events of all time. Now both new American and Chinese astronauts are preparing to recreate that thrill in the next decade.

The growing space economy is another reason. Satellite launches are becoming cheaper, encouraging most countries to want to get a toehold in space. The next steps may well be a base for humans and robots to work on the Moon, or scavenging trips to asteroids to bring back valuable elements.

Eventually, a few brave souls might head off to Mars. And some people actually see the future of humankind as an interplanetary species. Musk, for one, says his chief reason for building a spaceship capable of travelling far from Earth is that he wants to die on Mars, and not in a crash-landing.

But until then, we are left with second-hand views of the landscapes of planets beamed back by space probes. In half a century these have told us a great deal and had a huge impact on our imaginations. Before 1950, people really believed there were aliens living on Venus and Mars. Missions found the opposite – these are barren places. Now we are pushing farther afield for signs of life, to Jupiter and Saturn's moons and planets beyond the solar system.

What drives our fascination with space? And what is our relationship to these off-planet places? Are they becoming the playgrounds only of experts and elites and how can we all claim a sense of presence? How do we project meaning onto the skies? All these questions play in my mind. These are old questions, with deep roots.

This book is the result of my personal journey to answer some of those big questions. With such a vast subject, I've not been able to cover anything; indeed I've barely scratched the surface. But I've enjoyed finding out new

stories and loved hearing voices from history speak of their own longing for and fears of the stars and great cosmic unknowns.

The tales I've chosen highlight a mix of people, times and places. They aim to convey how people have felt about the cosmos, and they try to give a feel for the real places that surround us in the Universe. The book charts a journey starting with the nearby Moon before venturing further, through the solar system to the planets and then on to the stars, galaxies and beyond.

Within each section the flow is also largely chronological. It's not a conventional history of astronomy, but by the end you'll have a pretty good sense of how our knowledge about the Universe unfurled. I've skirted some well-known scientific stories, to look instead at their roots. I've tried to question conventional wisdoms, and often found them wanting. And I've tried to sample stories from around the world, beyond the West.

I've also picked out particular themes for each section. For the Moon, poetry and photography were key tools in allowing people to come to know this familiar body more intimately. In a sense, it is the play of shadows on the lunar surface that has attracted us to it so powerfully through history.

As for the other planets of our solar system beyond Earth, their less-familiar surfaces have acted as stage sets for our fantasies. I've looked to science fiction to shed light on those projections, as well as the evolution of ideas about their habitability and the chances of life elsewhere in the Universe.

The third section opens with a look at practical uses of the stars, for navigation and social control. It concludes with a

whistlestop tour of how twentieth-century physics transformed astronomy – and made it so abstract.

From the earliest records of tracking the stars and planets to wield power and control fate in ancient Babylon and China, to the baffling profusion of the twentieth century, when Mars fever and belief in extraterrestrial life ran alongside profound progress in atomic physics and theorising about the entire history of the cosmos, I've found more threads of continuity than I expected.

Take any current view and its roots go way back, deep in human history. Yes, there is a steady march of increased knowing, just it tends to lead us back to the same sorts of thorny questions. What is the nature of matter? How did the Universe begin? Why do humans exist? It's part of the human condition to want to know. And it drives us – to conquer Everest, the Moon, Mars, yes, but also to want to protect the rare gem of a planet we live on and share with other living organisms.

Even in a small way, I hope the perspectives shared in this book will underscore the important roles that the Moon, planets and stars play in all our lives, and have done across human history.

1

Shadows

To the Moon

Lunar attraction

We're all drawn inexorably to the Moon: so much so that people have developed entire technologies and risked death to set foot on it. And many still want to do so, aiming to set up Moon bases for research and perhaps even to settle there one day. Or at least visit.

But what drives that pull – to understand, go to, perhaps to possess the Moon? One thing is for sure, it goes back a long way. As the two dominant objects in our skies, the Moon and Sun have been revered for millennia in myriad ways. The physical attributes of the Moon and Sun have long shaped the lives of humans and other organisms on Earth, through cycles of day and night as well as the tides and the seasons. These cycles have brought us a sense of time, and of control over nature. But strong psychological factors are there too. The bright torch of the Sun spotlights our lives and has been said to burnish the truth. Meanwhile,

the soft glow of moonlight reveals shadier goings-on that would otherwise be hidden by darkness.

And perhaps surprisingly, ideas about both have had much in common across cultures. Themes soon emerge – the Moon is often portrayed as softer and more feminine than the strong and masculine Sun, but those very qualities can also give the Moon an edge in some cultures. Both have been worshipped and linked to the realm of the gods. Yet humans appear in these myths and stories too, for instance in the way that many cultures have perceived, or imagined, human features on the ‘face’ of the Moon. The heavenly pair have been widely used as proxies for earthly battles over life and death.

Playing such central roles in human societies, people throughout the ages and around the world have worked hard to learn ever more about the cycles of the Moon and Sun. The more about their timings skywatchers have pinned down, the more power that knowledge has commanded, and the narrower the range of people who are allowed to possess it has become. From predicting eclipses to possessing the kudos that comes from familiarity with profound phenomena like black holes, astronomers have acted as expert intermediaries between the wild forces of the cosmos and our everyday lives for centuries. Each fact-seeker among them adds a grain of sand to the dune of knowledge.

But others have been drawn to explore the cosmos in different ways, including poets and science-fiction writers, composers and sculptors, bringing to bear not knowledge but imagination. Many of us might be in that latter group, too, inspired by sublime telescope images as well as by thrilling coverage of rocket launches, space probes and astronauts’ low-gravity adventures. With a foot in both

camps, I'd like to try to bring these two views of the cosmos together.

To try to tease out these cosmic forces of attraction and how they have propelled humans for millennia, let's focus first on our nearest neighbour, the Moon, followed by some reflections on its twin and rival, the Sun. The Moon has a particularly special draw for people, I feel, as it is our nearest world, and the only one with a surface humans have actually stood upon, and will again.

Weightless and floating, the Moon's body appears unshackled from the Earth. Yet it is not free. It is bound to our planet by the intangible threads of the force of gravity.

And gravity is not the only force at work. I believe that tension, of being both connected yet isolated beyond reach, lies behind the Moon's attractive power. It fuels the emotional associations humans project upon it: love and yearning, loss and loneliness.

Yet, as a 'place', both real and in our imaginations, I think that the Moon cannot be considered entirely apart from the Sun's illumination. Sun and Moon are inherently connected. No sunlight and we wouldn't know the Moon was there. There would be no shadows. Switch off the Sun and the Moon's phases would be gone, its face blank.

As I'll relate, yearnings to understand the cycles and phases of the Moon have driven many scientific discoveries, from the distances to and sizes of the Sun and Moon to what each is made of. Studying the Moon's varying illumination by eye and through telescopes, sketches and photography, and eventually by visiting it, have revealed ever more about its landscape.

But first, let's consider our own experiences of the Moon and how it affects people, before tracing the long history of why and how we came to go there. In the end, it is the

shadows cast by its rocks, mountains and valleys that have impelled us to pen odes to the Moon and ultimately to set foot on it.

Tantalising glimpses

Any good gardener has a feel for the passage of the Sun. It's evident from watching the motion of shadows through the day and through the year. In mid-winter, at high latitudes, the Sun feels weak and can barely lift itself off the horizon. But as summer comes, it can't wait – it appears earlier and earlier and stays longer, until the solstice, when the longest day occurs, and it slowly takes again to its bed.

The Sun's daily passage casts blocks of bright and dark across my garden, spotlighting plants on one side and then the other, fuelling their growth. I sit out in the direct glare of the Sun when it's not too hot, before retreating to shade when it begins to burn. I sometimes catch the Sun's emergence at dawn, when the landscape is calm, the winds still, birds just starting their chorus. And I witness its passing, ideally glimpsed over the sea atop a clear horizon, bringing another calm to the end of the day, before the stars pop out like pins on a pincushion and weary humans make for their soft sheets.

Most of this solar watch happens subconsciously, noticed in passing as we go about our day. We're so familiar with it that it is ingrained in our minds and bodies. Our biological cycles are attuned to the Sun clock. We rise when it does, and sleep when it sets. Our body chemicals are stirred by its rhythms. It feels odd to fly to another time zone, where our system is out of kilter with the day. It's even odder to journey to a different hemisphere, where it jars that the Sun is in the 'wrong' place. I remember being unsettled by this

the first time I visited Australia from the UK: a nagging feeling of unease followed me around for months because I could not get used to the Sun being in the north and not the south. It didn't feel quite right somehow.

The Sun seems a happy celestial body to me, always jolly if occasionally a little tired. It's usually drawn with a smiley face at the centre of its warm rays.

But the Moon is different. I find the Moon altogether harder to read, and all the more emotive for that. Many people, me included, find the experience of a full moon especially powerful. It gives me a tingle up my spine and I find it hard to take my eyes off it, especially when it looks largest, hanging just above the horizon. This juxtaposition of the inaccessible Moon with our own world seems to pack a stronger punch than when the Moon sits bright and high and aloof in the black sky.

I'm drawn to moonrises, especially full moons. In London, I've regularly witnessed the full round emerging damp and sticky from the Thames mud while my bus crossed a bridge. Rushing into my flat, I'd try to keep watching the dramatic scene from the kitchen window, following its steady rise while I cooked, until it disappeared above the frame. Sometimes it rose confident and clear. On other nights it did battle with battalions of inky clouds before breaking free.

The Moon's cycle is fascinating to follow. It's often confusing, especially if you are in a city where the view of the sky is broken and compass directions are a jumble. On a given night I usually don't know where it is or whether it's there at all, lost amongst the rooftops. But if you return to the same place at the same time night after night you can start to learn its patterns. That's what I ended up doing during the COVID-19 lockdowns. Time seemed more abundant then, and the Moon's fickleness puzzled me.

For the first few months it evaded my predictions. Where was it? Oh, over there, not where I thought I saw it last time. What was it doing there? Over the year, I started to note where it rose on the landscape and was taken aback at how far it moved through the seasons. Full moons never appeared in the same place – in mid-summer they were far to the right, rolling up a hill and jumping into the sky out of a small tree. Then they wandered back to the left each month, downhill, until in mid-winter the bright disk of the Moon was smothered for a while in a conifer, only emerging later in the night. This difference wasn't subtle: how had I not noticed it before?

The Moon's slow fattening and thinning, from new to full and back again, is also captivating. No two nights are the same. Stepping out of my office just after sunset one chilly winter's evening, I recall being delighted by a thin crescent moon hanging ahead of me, in the west, low in the sky. It was so sharp and crisply etched that passers-by on the street commented on the sight. Just to its right was another bright point, a planet, perhaps Venus? Over the next couple of hours the dazzling pair arced across the sky, only to disappear behind the rooftops and eventually over the horizon.

The following night, I looked for the Moon again. There lay the bright planet ahead. But now the Moon lagged farther behind. And it was transformed. A crescent still, yes, but now cocooned in a translucent ball of ice crystals, like an embryo in a glass womb. Beautiful again, yet utterly different. A bauble rather than a fine porcelain shard.

On the next night I only snatched the briefest glimpse of the Moon, lost amongst the dark hulks of buildings, tangled in fluorescent signs. Its planetary companion stood alone in the west, waiting.

Clouds then interrupted my moon-watching for a few nights, but about a week later, the evening skies cleared. I looked again. But where was it? I spun around, chin in the air. Eventually I saw it – above my head, high, a little behind me. This time its belly was fuller. Again it sat in a balloon of scattered light.

Another week on, the Moon surprised me once more. Looking up from my computer screen I saw it rising blatantly through my office window. Now it was in the east, opposite the setting Sun. It was showy and full, confident, in a pink evening sky. Teasing me.

One month after my first sighting, I was pleased to greet the crescent moon outside the front door, back from its celestial loop, standing close again to its companion planet. Had I cracked its secret? Almost, as long as I kept a watch. But the Moon has a lot of secrets. Stop watching for a moment and it escapes again.

Here is the technical explanation. The Moon ‘rises’ around fifty minutes later each night than the night before: that is to say, as the Earth and Moon turn, it becomes visible at a different time, which puts it somewhere different on the skyline. If you look at it at the same time on consecutive nights, it appears 13 degrees farther to the east each time. It takes 29 and a half days for the Moon to go through all its phases and return to the same place in the sky. This is the length of the lunar month (also known as the ‘synodic’ month).

But the Moon is also travelling with the Earth as the Earth revolves around the Sun, and the Earth is itself turning relative to the starry backdrop, Earth revolves one extra time during a year. So, the Moon ‘needs’ to turn a little more to repeat its phases when viewed from Earth. Relative to the

stars, it actually completes an orbit of the Earth every 27.3 days (this period is known as a 'sidereal' month).

The Moon's phases occur when different parts are lit by the Sun. During a new moon it appears dark; we only 'see' its shaded side, which is present in the night sky but too dark to actually spot. The Moon lies between us and the Sun (we don't necessarily see the Moon eclipse the Sun because the two don't travel on exactly the same paths across the sky. Their orbits wobble slightly).

As the Moon spins around the Earth, a little more of the sunny side is revealed. Just after the new moon, the faintest slither of a crescent appears. Its belly then fattens, or 'waxes' – the perfectionist in me enjoys the Moon when it is cut exactly in half. And after a fortnight we see a fully round Moon. Now the Moon is behind us, its face completely illuminated by the Sun.

Earth lies in between, usually slightly displaced: but when all three bodies line up perfectly, and Earth casts its shadow on the Moon, we may witness a lunar eclipse.

After the full moon, the Moon spins on along its orbit, and the phases reverse. Its disk withers, or 'waned', until it disappears again. Another new moon restarts the cycle.

Muse and madness

Psychologically speaking, the Moon's repetitive shape-changing can be something of a solace. It is reliable, always punctual. But the Moon is also moody, a drama queen who cloaks herself sensually in the available atmospherics. Factor in nocturnal darkness, and it's no surprise that the Moon is so beloved as a muse of poets; some have said she is poetry itself. While sunlight is exposing and cleansing, what takes place in moonlight is far more mysterious.

Daylight is transparent. Lunar illuminations allow for subtlety and subterfuge.

Poets know these many characteristics well and give the Moon emotional airs. Some have written of moonlight as casting joy and hope, caressing romantic trysts, for example. And the Moon itself can seem playful, escaping the tangled branches of trees and rising into the sky like a 'child's balloon, forgotten after play', as poet T. E. Hulme described it. After all, the Moon plays a four-week game of hide and seek. It follows us when we travel, scudding across landscapes beside our moving train or nestling in airplane windows as we fly.

Other poets have painted powerful pictures of the Moon's many personae. When draped in mists, Oscar Wilde saw its yellow slither as soft, a 'withered leaf' blown across the twilight sky. On the other hand, Mina Loy likened its harsh white glare to a 'silver Lucifer' serving 'cocaine in cornucopia', a 'nocturnal cyclops, crystal concubine'. Magical words indeed.

Often, though, poets portray moonlight as carrying a tinge of sadness. To Wallace Stevens, it is the 'mother of pathos and pity'. Percy Bysshe Shelley thought the Moon lonely, plodding alone through the heavens: 'art thou pale for weariness'? Walt Whitman shone moonbeams on the carnage of war: 'pour softly down night's nimbus floods on faces ghastly, swollen, purple'. Ford Madox Ford wished to imagine 'a moonlight in which there would be no machine guns'.

And lunar tales are full of thwarted lovers. The ancient Greek female poet Sappho (who lived from roughly 630 to 570 BCE) saw in its nightly passage a reminder of mortality and lost love: 'Tonight I've watched the Moon and then the

Pleiades go down. The night is now half-gone; youth goes; I am in bed alone’.

The ancient Greek Moon goddess Selene suffered endless unrequited love as her mortal beau, the shepherd Endymion, was put into an eternal sleep. Artemis the huntress was another Greek goddess with the Moon as her symbol. She regretted killing her true amour, her fellow hunter Orion, and remained chaste in remorse. Roman moon deities Luna, Diana and Juno were similarly deprived of passion.

Yet Artemis was not a depressed or destitute figure. She was heralded as a bringer of light – imagine the blessing of a bright moon when there are no streetlights. And she assisted women in childbirth. By contrast, the Greek Sun god Helios was kept far too busy riding across the sky in a gold chariot controlling day and night, truth and sight.

As these examples show, while the Sun is usually portrayed as masculine, the Moon is often linked to the feminine and to fertility and the forces of life. The Moon’s swelling belly mirrors that of a pregnant woman, and moonlight has long been said to help women to conceive. Ancient peoples noticed the similar 29.5-day timings between lunar cycles and average female menstrual bleeds. The word menstruation comes directly from the Latin root ‘mensis’ meaning month, which had its own roots in the ancient Greek ‘mene’ meaning ‘moon’. Even goddesses had periods: in ancient Mesopotamia, a high priestess called Enheduanna recorded those of the moon goddess Ningal. Many cultures have made menstruating women hide from daylight or stay out of the public realm. They might have found solace in the Moon.

But lots of cultures have different ideas of the Moon’s gender. In Japan, there’s a Sun goddess (Amaterasu) and a

Moon god (Tsukoyomi). Similarly, the Norse religion had a female god of the Sun (Sól) and male god of the Moon (Máni), who are siblings. There's so much power over life on Earth between them that all their qualities can't be attributed to one sex or the other.

Some plants open their flowers or adjust their leaves to catch the Sun's powerful rays - sunflowers track the Sun's motion through the day, for example. But some flora and fauna also seem to respond to the Moon. White 'moonflowers' are more visible in twilight and moonlight: others open during the night and spread scent to attract particular moths and insects. Some corals spawn within days of a new or full moon, sending fertile milky clouds out into the currents. Certain fish and crabs also time their spawning or trips to the sea with the lunar cycle, although for these inhabitants of the sea this may be as much to do with the convenience of high and low tides (indirectly a result of the Moon too, of course) as with the Moon's gaze.

That brings us to another of the crucial roles the Moon plays in life on Earth. While the Moon's attractive force is too small to be perceived by a human or fish, unlike the strong pull we feel towards the ground, it is enough to influence the flows of the oceans. The Moon draws their waters towards it, causing the seas to bulge and deepen on the near and far sides of the Earth. As the Moon spins about its axis and orbits Earth, these fluid bulges turn along with it, swelling and draining the oceans twice a day. Similarly, when the Moon was younger, its tidal pull from Earth distorted its shape and made it a little elongated. The Moon lost gravitational energy as heat while as it flexed, so that over billions of years it has become locked with one face turned towards us. Earth and Moon are locked in a tidal waltz.

For centuries, astrologers, philosophers and writers have also linked lunar cycles to human wellbeing and fate. Whereas the Sun is purportedly direct and extrovert, the Moon is supposedly shy and represents our unconscious desires. It metaphorically harbours our instincts, insecurities and fears.

The far side of the Moon, permanently hidden, represents the unknown, the inner world. 'Every one is a Moon, and has a dark side which he never shows to anybody', as Mark Twain wrote. It was not until the space missions of the twentieth century that humans saw the far side of the Moon. In 2019, a Chinese mission dropped an uncrewed lander there. It carried some cottonseeds with it, in an experiment to see if they could germinate, within a small container hosting soil, water and air, to perhaps later support astronauts at a Moon base. Out of our view, one sprout became the first plant to grow on another world.

Indian Vedic astrologers have believed that the changing phases of the Moon mirror our own ebb and flow of energy. Someone's personality reflects the lunar phase at their birth – a waxing moon heralds an outgoing character, a waning one introspective.

In classical Rome, men cut their hair when the Moon was waxing, to encourage luxuriant growth and avoid baldness. But the Moon was also linked to certain diseases, especially to sudden fits of epilepsy. People prone to seizures slept with their faces covered to protect themselves from the light of the Moon. Moonlight was also thought to induce madness, or 'lunacy' (from the Latin word 'luna', moon).

All these connections came together in Roman tales of men becoming wolfmen when afflicted by a moon disease. The victims convulse and rush from their homes. Their hands clench like claws and they howl in the streets and roll

on the ground. The next morning they may return, unaware, to their normal selves.

The Roman novelist Petronius wrote in his *Satyricon* of one such experience. The slave Niceros travels out of the city one evening under a bright moon, in the company of a soldier. They rest at a point in the road flanked by tombs. To Niceros's surprise, the soldier strips off his clothes. He turns into a wolf, running howling into the woods.

Ancient Greek philosophers including Aristotle and Pliny the Elder believed that susceptible individuals were driven insane when moonlight prevented them from sleeping. 'Frantic behaviour, unreasonableness, constant restlessness and mischievousness' rose and fell with the phases of the Moon, according to sixteenth-century Swiss alchemist and physician Paracelsus.

Inmates of asylums, such as the infamous Bethlehem (or Bedlam) hospital in London, were chained and flogged during certain phases of the Moon, a practice eventually outlawed in 1808. Moonlight 'frightens one, rejoices another, and agitates all', noted nineteenth-century French physician Jean-Étienne Dominique Esquirol.

Many novelists and playwrights took up the theme. John Milton wrote in *Paradise Lost* of 'daemonic phrenzy, moping melancholy and moonstruck madness'. Shakespeare wrote of 'lunes', or mad fits of distraction, in *The Winter's Tale*, while in the play bearing his name Othello affirms: 'It is the very error of the moon; she comes more nearer Earth than she was wont, and makes men mad'.

Perhaps water within the body was the reason, thought Pliny the Elder back in the first century CE. Heavy dew on moonlit nights must make the brain moist, he wrote. Like the oceans, damp bodily tissues must be susceptible to the

pull of the Moon. Similar ideas of 'biological tides' have ebbed and flowed through the centuries.

Moon worries still hold sway today. In one study in 1985, half of university students interviewed believed that people act strangely during a full moon. In 1995, four-fifths of mental health professionals thought the Moon alters behaviour. And in 2007, some UK police forces posted more officers on nights with full moons to tackle presumed increases in crime. Yet no statistical evidence supports any of these cases. Certainly, gravity doesn't change with the phases of the Moon; they merely provide a change in illumination.

But there may be grains of truth in the idea that years ago, before streetlights, it might well have mattered for people's safety whether the streets were light or dark. For example, in eighteenth-century England, to avoid robbers and unseen potholes, one elusive group of intellectuals chose to meet monthly on nights with a full moon to discuss literature, politics and science over dinner. The members, who included the scientists Joseph Priestley and Erasmus Darwin as well as industrialist Josiah Wedgwood and engineer James Watt, dubbed themselves the Lunar Society of Birmingham.

Even modern cities take on a different character under darkness. When we can't see far around ourselves we feel more cocooned, walled off by the darkness in our own world. Nights are more private. We can be ourselves, dress more flamboyantly, pile on the make-up or skip it: no passer-by will see. Nocturnal time seems less regimented, more fluid. Only the immediate matters, at least until we must catch that final train. No bosses watching, night work is undertaken by our wits. In bars and restaurants, enjoyment wins over necessity. We're more likely to lose our

inhibitions to alcohol, lose ourselves in a film, dance wildly, laugh, eat too much at night. Questionable activities, such as prostitution and drug-dealing, like to hide in the dark, though talk of more crimes after dark are mostly myth. Burglars are just as likely to act during the day, when it's easier to see and people are out.

Like werewolves, ghosts and vampires prefer night to day. Night-time dreams project us into hallucinatory worlds, where we can fly, or where animals speak to us. This is why shamans stay up at night to commune with spirits and gods. Like nocturnal animals with heightened senses, they act as a conduit between cosmic energies and communities.

Shakespeare used the cloak of darkness to release the prankish world of fairies in *A Midsummer Night's Dream*. Romeo and Juliet run away after nightfall, although to confusion and tragedy. The contrast between light and dark heightens the clash between the searing brightness of young love and the black despair of its loss. Romeo is 'day in night': Juliet is like the Sun. But she protests when Romeo swears his love by the 'inconstant' Moon, 'that monthly changes in her circled orb, lest that thy love prove likewise variable'.

Yet, though the Moon's cycles change, its face is constant. Gravity has locked the body in its embrace, swinging it around Earth while it is always looking straight at us. That's why the Moon is a unifier. Wherever you are, you can imagine your loved ones looking up at the same sight. You are instantly connected, yet reminded also of that distance.

Chinese poems have long used the Moon to evoke home sickness. Across such a vast country, many people are used to travelling long distances to visit friends and family or for work and trade. One of those travellers in the eighth century CE (during the Tang dynasty) was the wandering poet Li Bai.

‘Quiet Night Thought’ is one of his most famous works, still taught in schools today:

Moonlight before my bed
Perhaps frost on the ground.
Lift my head and see the Moon
Lower my head and I miss home

Li Bai, also known as Li Bo, was himself named after a celestial wanderer, the planet Venus. His mother called him TaiBai, ‘Great White’, as the planet was known in China, after she dreamed of a falling white star. Li’s family were merchants on the Silk Road and lived near Chengdu in Sichuan province.

Li was a Taoist, and observant of the powers of nature. He was also a wine-lover, and member of a group known as the ‘Six idlers of the bamboo brook’, dedicated to literature and wine.

Fittingly, legend has it that Li Bai drowned after reaching, drunkenly, for the Moon’s face reflected in the Yangtze river.

Another Chinese tale, which tells us how the Moon got its face, is still celebrated today in China’s mid-autumn festival. In late September or early October the Moon comes closest to Earth and appears exceptionally large and bright, symbolising fruitfulness and perfection. Across China and Asia, families gather under this ‘harvest moon’ to feast.

Daughters and sons, sisters and brothers travel back to their hometowns to dine with their families, often under the stars. It is traditional to exchange ‘moon cakes’, with whole yellow egg yolks representing our satellite encased in decorated lotus-seed paste. Couples walk in the moonlight. Paper lanterns are lofted. Dragons dance in the streets.

The origins of the Chinese mid-autumn festival are hazy. They date back thousands of years to ancient China when emperors worshipped all things celestial, offering sacrifices to the Moon in autumn and to the Sun in spring. This old story, of which there are many versions and the roots are lost, also illustrates how our longing for the Moon echoes feelings of separation from the one you love.

Long ago – so the myth goes – ten suns circled the Earth. Their heat scorched the land, leaving the people poor and starving. A great immortal archer called Hou Yi decided to act. He took his bow and arrows and climbed to the summit of a mountain, from where he shot down nine of the suns. But in doing so, Hou Yi upset the powerful Jade Emperor god, who turned Hou Yi and his wife Chang'e into mere mortals.

Chang'e was miserable living on Earth, and Hou Yi set off to find a way to return to the skies. The Empress of Heaven gave him a phial of tonic, one sip of which would turn him and his wife back into celestial beings. Hou Yi hurried home and handed the phial to Chang'e, who immediately drank the potion. Instantly she flew into the sky.

Hou Yi was devastated to find his wife gone. He looked up and saw the fleeting shadow of his wife in the Moon's bright face, out of reach.

Since then, each year, when the full moon is exceptionally clear and beautiful, people in China pray to Chang'e for love, fortune and peace.

China's romance with the lovely lady in the Moon is still strong. Its space agency is planning to send a real person to visit her some time in the 2030s, as the culmination of a series of lunar missions named after her. So far, a pair of Chang'e spacecraft have photographed the Moon's face to look for her traces. Others have landed and delivered a

rover to the surface. And one has scooped up rocks and brought them back to Earth.

China's lunar rovers are named after another mythical character, Yutu the Jade Rabbit, who lives with Chang'e on the Moon. The name was chosen by the public in an online poll. Chinese observers have long imagined an outline of the crouching hare on the face of the Moon, its long ears and shadow evident in the Moon's dark markings, grinding herbs with a pestle in a mortar to make an elixir of life for Chang'e to bring her back to Earth.

Such stories date back at least to the third century BCE, in ancient Chinese texts such as the mythologies collected in *The Classic of Mountains and Seas*, and the anthology *Chu Ci* ('Poems of Chu'). Other lunar animals also crop up in Chinese and East-Asian folklore, including a toad, monkey, otter and fox. Crows, meanwhile, were often associated with the Sun.

Folk tales of rabbits in the Moon crop up surprisingly often elsewhere in the world. It might be just coincidence – people see similar shapes in the lunar patterning. Or it might reflect the Moon's frequent association with fertility.

Ixchel, the Mayan goddess of the Moon – and of love, gestation, medicine and textiles, wife of the Sun god Ak Kin – was often depicted with a rabbit by her side. A rabbit shared his food with the Aztec god Quetzalcoatl, saving him from starvation on a long journey, is supposedly elevated to the Moon, its shape remembered in light. A Cree legend in Canada and the northern United States tells of how a young rabbit wanted to ride to the Moon. He caught a lift there by hanging on to the legs of a flying crane, stretching them in the process.

Europeans and Americans more often talk of there being a 'man in the Moon'. Like Chang'e he has usually been

banished there for some misfortune or misconduct. To the Romans he was a sheep thief. To Germanic cultures a woodcutter found working on the Sabbath. The Haida people of western Canada see the figure as a boy gathering sticks, punished for being too lazy to go out to collect firewood at night.

The man in the Moon can be comic, as in Georges Méliès' 1902 silent film, *A Trip to the Moon* (*Le voyage dans la lune*), where the rocket capsule hits him roundly in the face. Inspired by science-fiction writer Jules Verne's 1865 novel *From the Earth to the Moon* (*De la terre à la lune*), the film relates how a group of explorers clad in top hats and tails journeys to the Moon.

Years later in Berlin in 1929, German cinematographer Fritz Lang released his own film, *Woman in the Moon* (*Frau im Mond*). The screenplay, which was written by Lang's wife Thea von Harbou, returns to the age-old theme of desire – for love and loot. In a way, it is a twist on the Chinese tale of Chang'e as a man and a woman end up stranded on the Moon. The pair caress as the movie ends: two more homesick humans add their marks to the Moon's face.

Yet, there's far more to the Sun and Moon if you watch their cycles. Their repetitions have driven human culture around the world, as well as those in the natural world.

Cycles and symbols

The Moon's phases, and the shifts in the positions of the Sun and Moon relative to the horizon, have been tracked by societies since prehistory. Evidence stretches as far back as archaeological records go. For example, regular sets of notches marked on mammoth tusks, like tick marks on a graph which appear to count out repeating phases of the

Moon, have been found in Paleolithic settlements in Ukraine dating from around 15,000 BCE.

The positions of the rising and setting Sun and Moon are significant, especially on the longest and shortest days of the year, the solstices. These positions have often been used to define key directions, such as the cardinal points – east, west, north and south. The points in the landscape where the Sun and Moon appear and disappear have particular significance too. They helped people define directions to describe their environment as well as to set out calendars for planting, hunting, rites and ceremonies.

For example, in the western USA, different groups of Pueblan and Hopi peoples used the Sun to define directions and flag key dates. The Acoma defined six directions relative to the sunrise, from where they said the first human beings rose from the underworld: east to the front, west behind, north to the left, south to the right, as well as below and above.

The Hopi system is tied more precisely to the positions of sunrise and sunset at the solstices. ‘Sun watchers’ monitored the passage of these points clockwise around the horizon. For half the year, from winter to summer solstice, they noted the place of sunrise as the days lengthened. Then they switched to tracking sunsets as days shortened and darkness took over. Different leaders or clans followed different legs of the Sun’s path, and dates were set for planting crops or ceremonies by noting when a sunbeam passes through a chink between rocks or an aperture in a wall. The Hopi also counted days and observed the Moon.

Sunrises and sunsets are much harder to pin down in mountainous regions, where elevation can obscure the Sun. Positions and timings differ depending on where you view it from, deep in the valley or high on a hill. In the Caucasus

mountains of central Europe, villagers built stone platforms or 'sun nests' on summits to monitor the Sun's movement reliably.

Thousands of years ago, marking sunrise on the winter solstice was an important rite across Europe. It heralded the onset of the coldest season as well as the gradual lengthening of days leading to spring. For example, the prehistoric tomb of Newgrange in County Meath, Ireland, consists of a large circular mound, eighty metres across and twelve metres high, with stone walls and a grassed roof surrounded by a ring of standing stones. It dates to around 3,200 BCE; human bones and the remains of votive offerings have been found within. Its entrance is aligned with the rising Sun on the winter solstice. The first rays shine through a hole in the roof to illuminate the inner chamber on that day. Similar sites are found in Brittany in France, Orkney in Scotland and Wales.

Arrays of standing stones, from Stonehenge in Britain to Carahunge in Armenia, have also been interpreted as ancient solar observatories on the basis of alignments between the stones and the position of the Sun on key days. But we still know little about how the sites were used in practice. The stones themselves may have had other symbolic functions, such as providing temporary resting places for the souls of the dead before they embarked on afterlife journeys. The west, towards the setting Sun, was often associated with death. Souls descended like the Sun into the underworld.

Christian churches still exploit similar lighting effects. Across Europe, church doors usually face east, with the building aligned on an east-west axis. Special paintings inside or particular stained-glass windows may be illuminated on certain saints' days. The interior of Gaudi's

Sagrada Familia cathedral in Barcelona is designed to be illuminated spectacularly around sunset, in particular at the winter solstice.

In most gothic cathedrals, the top of tall stained-glass windows appears brightest, the colours richest. Sunlight streams into the upper reaches, whereas the lower levels might be shaded by outside trees or adjacent buildings. Gaudi strove for the opposite, imagining 'light gliding over the windows like water over pebbles'. Textured but clear glass in some of the highest windows sheds rainbows. And the leaded glass panels below are designed to give an impressive light show at sunset, especially around the winter solstice.

Visiting the cathedral late in the afternoon in autumn, I've seen the western windows of the Sagrada Familia glow in fierce warm colours, shades of red, orange and yellow. As the Sun descends, its rays approach the horizontal, projecting red light first on the floor, then rising up the columns like flames. The pattern of the rose windows is projected in light against the stone vault. And the fire reaches right across the nave, where it is quelled by the cool blue and green panes of the eastern windows, which are themselves lit quietly at dawn.

The archetypal power of the Sun or Moon has also been captured in symbols. Merely drawing, touching or holding a representation can potentially direct some of this natural energy for human purposes.

The Moon is often shown as a spiral, hinting at its ever repeating cycles. Shells and pearls are synonymous with it, and horned animals are reminiscent of the Moon's crescent. Snails peek out from vulva-like openings in coiled shells. Snakes too often symbolise fertility and the Moon, as do bears that appear and disappear with the seasons.

The Sun is often represented even more simply, by a circle or a series of concentric rings. Sometimes the circle is scored through with a vertical cross, representing the cardinal points of north, south, east and west. Linear rays, as in a child's cartoon drawing of the Sun or the spokes of a wheel, as well as dotted rings, sometimes emanate.

Simple solar patterns like these appear in rock art from western Europe to the Americas. In some sites in the Alps, solar circles are carved alongside spear-carrying figures and running deer, suggesting the picture is connected to seasonal hunting. In Uzbekistan today, four-pronged stars, concentric rings and rays are still stamped onto circular loaves of flat bread to symbolise the Sun. The richly decorated loaves are revered. Broken and shared by hand, they are a focus of each meal, especially at celebrations of births and weddings.

Ships are another common symbol of the Sun's passage across the sky. Scandinavian rock art depicts ships with their prows pointing towards sunrise. Similar scenes adorn petroglyphs on the opposite side of Europe, in the archaeological reserve of Gobustan, Azerbaijan, south of Baku. Perhaps ceremonial boats once set out to greet the first rays of the Sun over the Caspian Sea.

Solar and lunar symbols may be combined as well. The bronze Nebra sky disk is inlaid in gold with a solar disk and crescent moon set amongst dots thought to represent stars. Dated to around 1,600 BCE, the disk was discovered near that town in Germany in 1999 by two metal-detector enthusiasts.

An eye is another common format. Maybe the ancients thought a solar eclipse looks like an eye, or it might have reminded them of the power of 'all-seeing' deities. Many Romanian houses, for example, are decorated with these

solar-eye symbols as lucky charms. There are many variants, but typical ones include a circle, representing the Sun's disk, with its limbs intersected on either side by two arcs, representing the Moon and its phases. Some also have rays projected downward, like lashes, and curves above, like an eyelid or brow. Similar patterns have been found in Transylvania, at Knossos in Crete and on clay tablets dating back 6,000 years from Jemdet Nasr in ancient Mesopotamia (now Iraq).

It was common to describe the Sun and Moon as the eyes of the gods in ancient Mesopotamia. The concept of the 'evil eye' was also common in Greek lore: the gods were always watching you. Later, Christians adapted the eye symbol to become the eye of the Lord, appearing in paintings as a circle inside a triangle surrounded by rays.

Animals too took on the symbolic power of the Sun and Moon. For example, in China and many Asian cultures, the crow evokes the Sun and is seen as a bearer of light and life. Arctic and Native American cultures have a similar link: in the mythology of the Haida people of British Columbia in Canada, Raven created the world and stole the Sun to give this treasure to humanity.

Thus, early civilisations tried to connect themselves with the power of the Sun and Moon, as benevolent and protective forces. Symbols were a form of shorthand. But the connections and stories grew even more elaborate as they were incorporated into religions and to run entire civilisations.

Sun worshippers

While many civilisations had a sun god of some kind, few made it central to their religion, but the ancient Egyptians

were one that did. The Egyptians revered the life-giving force of the Sun which, according to their myths, created plants and animals. They also heralded its ability to set natural order, such as the annual flooding of the Nile, which brought fertility to the desert. Ancient Egyptians believed the world emerged from cosmic slime, much as birds, crocodiles and amphibians were born amongst the marshes fringing the Nile.

The Sun god Ra himself emerged from an egg or lotus flower, or alighted like a bird on the first land. The first light turned the sky gold and the primeval waters brilliant blue, like lapis lazuli. One image of the first sunrise is of a blue lotus rising above the surface of the primeval ocean. As the day progressed, Ra became older, growing from a child in the morning to a full-grown man at noon. He became increasingly weary through the afternoon until he was an old man in the evening. Sunset was equivalent to death, when Ra descended to the underworld. He moved through its caverns until the Sun was reborn at dawn. To the Egyptians, each sunrise was thus a new beginning for the cosmos.

In early stories, Ra died each evening by being eaten by his mother, the sky goddess. He was replaced by multitudes of stars. In the morning, the reborn Sun god ate all the star gods. Their blood stained the dawn red. Life came of death.

Other sources envisaged the Sun in an eternal voyage across the skies and then below Earth. At sunset, the day boat of the Sun left the upper sky to be replaced by the barques of the Moon and stars. The night boat carrying the Sun god was towed over water and sand through 12 regions of the underworld, where the Sun god had to subdue monsters embodying darkness and chaos.

In other strains of Egyptian tradition, the disk of the Sun was also envisaged as a goddess, or sometimes as the 'sole

eye' of the cosmic creator god, Atum, who, along with his female counterpart Atumet, kick-started the whole Universe into being. The eye goddess was also described as the daughter of Ra, and had a fierce personality. The eyes of Horus, the sky-falcon deity, were also linked to the Sun and Moon.

The Moon's cycles were linked to the killing and mutilation of another Egyptian god, Osiris, in a fight. The full moon represented the whole body of Osiris: evil triumphed as the Moon waned, but good returned with its waxing.

In the early eras, such as the period of the Old Kingdom (approximately 2,700 to 2,200 BCE), Egyptian kings, or pharaohs, were considered earthly representatives of the Sun god, Ra. The gods supposedly lived in a mythical landscape that mirrored Egypt geographically. And temples were set out like stage sets so that ritual re-enactments of stories could take place. The most powerful pharaohs, like Khufu (Cheops), wanted even bigger temples and erected huge pyramids: Khufu's tomb is the great pyramid at Giza.

New Sun cults arose during the New Kingdom era (roughly 1600 to 1100 BCE), when Egyptian rule spread to Syria, Palestine and Nubia. At Thebes, the creator god Amun was united with the Sun god to become supreme 'king of gods', Amun-Ra. Pharaoh Amenhotep IV and his chief wife Nefertiti were dedicated to the cult of Aten, a form of the Sun god represented by the solar disk. Other deities were sidelined for a time, but his son Tutankhamun reversed this change, reverting to Amun-Ra as primary god.

Egypt became part of the rise and fall of a series of great empires over the next millennium, suffering invasions and occupations by Libyans, Nubians, Assyrians, Persians and Greeks. These new rulers borrowed from and reworked local mythology to govern the people – myths carry much more

easily across languages than, say, poetry, which is hard to translate. Stories can also convey important messages irrespective of how they are told.

When the Greek essayist Plutarch visited Egypt in the first century CE, he became fascinated by these myths. He didn't think they were describing real events, but considered them to contain universal truths. His version of the Myth of the Eye of the Sun includes descriptions of Egyptian culture and even associated animal fables. We typically associate these with Aesop, a Greek slave of the sixth century BCE, but similar stories were being told millennia before in other cultures.

The Myth of the Eye explains why the Universe's creative and destructive forces must be balanced. It starts by describing how, just after the cosmos was created, humanity came forth from tears shed by the Eye goddess. People and gods then lived side by side under Ra's rule. But quarrels broke out as the Sun god aged and his authority waned. His female counterpart, the Eye goddess, became angry and ran off into the desert in the form of a lioness: this is another ancient tale of a strong female force.

Ra dispatched other gods to find her and persuade her to return. One, often the Moon god Thoth, spied the angry goddess, with flames spurting from her eyes and nostrils. Terrified, he 'quivered like a grasshopper'. But he tried to win her over, by regaling a fable, the story of the lion and mouse.

One day, the fable goes, a mighty lion walking in the mountains met a panther in a sorry state. 'Who pulled out your fur?' he asked. 'Man,' the panther replied. The lion had not heard of man, but resolved to find whatever it was and punish it. Wandering on, he encountered chained horses, cows and oxen. 'Who did this?' he asked. 'Man,' they

replied. Then, suddenly, a mouse ran under lion's paw. It begged the lion not to crush him, for he was too small to make a tasty meal. Mouse promised that if the lion let him go, he would one day help him in return.

So the lion let the mouse go, and continued on his journey. But, oh! He fell into a pit. Man had set a net over it and the lion was trapped. He struggled for hours until, at night, along came the mouse and gnawed through the nets and ropes to set the lion free. Mouse climbed into his mane and they headed back to the mountains together.

The principle? That the destructive, chaotic anger of the solar eye must be balanced by truth and justice to maintain cosmic order. Eventually Thoth lures the goddess back, whereupon, seeing the music and dancing that greets her, she becomes calm and 'beautiful of face'.

In another myth, as he ages, Ra transforms into many heavenly bodies. He creates 'fields of paradise' for the spirits of the dead and the gods who live in twilight. He calls the Moon of Thoth into being to rule the sky as his deputy.

Using myths like these, Egyptians were able to explain the patterns of the natural world. Their rulers further used them to co-opt the power of the Sun, Moon and other celestial bodies. And Egyptian society shaped its rituals around these stories, to try to control nature and to fit themselves in with it. Just as humans aged, so did the cosmos. Just as humans died and entered the afterlife, so came nightfall and the dawn of a new day.

Moon magnates

The ancient Mesopotamians found more power in the Moon's shifting cycles than in the steady torch of the Sun. Their Sun god Utu (also known as Shamash) was great and

powerful, charging around the sky in his chariot: but he was also a bit bland, shining benevolently down during the day. At night, Utu plunged underground into a pitch-black tunnel, from where he emerged at dawn. In the epic story of Gilgamesh, the hero is advised to run as fast as he can to reach the end of the tunnel before the Sun makes its nightly dive, or he will 'find no refuge from its deadly fire'. The Sun is either very much on or off.

Lunar cycles spoke far more to the opposing forces of nature that shape human lives: battles of light against darkness, the dramas of birth and death, creation and destruction. Mesopotamians exploited the strong link between the feminine and the Moon to serve the king: the Moon was so important to Mesopotamian life that the high priestesses that served the Moon god Nanna came from royal blood, usually being daughters or sisters of the king.

One such priestess – not the first, but the most famous – was Enheduanna. Around 2300 BCE, Princess Enheduanna took up this role in the Sumerian city-state of Ur, in present-day Iraq. She was the daughter of King Sargon of Akkad, the first king to unite and rule over the whole of Mesopotamia, the land between the Tigris and Euphrates rivers, by combining the regions of Akkad in the north and Sumer in the south. He sent his daughter to Ur to cement his power in the south, as priestess in one of the largest temples in the land.

Enheduanna left nearly fifty poems and hymns for Nanna and other deities, which were highly valued in her time and copied for hundreds of years afterwards. She is one of the oldest named writers in history, and her words are evocative still today.

We know about Enheduanna from thousands of clay tablets unearthed from Ur's remains by archaeologists in

the 1920s. They were buried for millennia beneath a vast pile of sand. The excavations themselves were a struggle: no sooner had the archaeologists swept an area clear than violent sand storms sprung up and reburied it. At other times it rained so hard that the desert turned into a huge lake, cutting off the camp.

One of the archaeologists, Max Mallowan, painted a vivid picture in his diary: 'There were some days when food, drink, and everything else, including bathwater and beds, were sand-laden.' These conditions must have been unchanged in four thousand years, he noted, 'for we often found that the teeth of the ancient inhabitants had been ground down through masticating grit'.

But we don't just have Enheduanna's words; we have images of her too. A panel on a carved circular stone, twenty-six centimetres across, shows Enheduanna in the middle of a temple procession. Shown in profile, she wears a long, tiered dress and a conical, roll-brimmed crown. Her hair is free, curls roll down her back, and her hand is raised in greeting. Two attendants ahead of her, one naked, present an offering at an altar. Two more follow behind. The disk is chiselled alabaster, white as the full moon.

Enheduanna would have performed rituals like this to tame ferocious natural forces in this arid yet storm-beset land. The temple was at the heart of the city-state and employed most of the population. Enheduanna would have managed the staff – cooks, bakers, smiths, leather-workers and stonemasons. She also controlled the finances, buying and selling goods and handing out salaries and loans. The temple ran the agricultural lands around the city, from planting and harvesting crops and looking after livestock, to maintaining fisheries, reservoirs and irrigation.

And Enheduanna must also have been one of the first astronomers. Observing the Moon, Sun and stars, along with sundials during the day, would have guided their time-keeping.

The Mesopotamian year began with the sighting of the first crescent moon after the spring equinox, around March 21, when the lengths of day and night were matched. New moons were celebrated each month, particularly after the autumn equinox in late September, which coincided with the harvest.

The Mesopotamians recorded everything meticulously on clay tablets, in cuneiform script composed of many tiny wedge-shaped imprints. Positions of the Moon and planets were reported each day alongside notes about the weather and price of wheat and corn. Their astronomical records are still the oldest contiguous observations of the sky made, spanning more than six hundred years daily without a break. Enheduanna would also have looked for unusual events in the sky to report to the king as omens.

Acting as 'earthly wife' to the Moon god Nanna, Enheduanna channelled messages from him through her body, taking part in a special 'marriage' ceremony with him after harvest for example. In other parts of the temple she looked after Nanna's heavenly partner, the Moon goddess Ningal, and their daughter, Inanna, Queen of the Heavens, embodied in the planet Venus.

Nanna (also known as Sin) was associated with wisdom about the world, and astronomy in particular. His sanctuary at Ur was known as the 'house of the great light' (E-gish-shir-gal). And he was often depicted with a beard of lapis lazuli, a bright blue stone symbolic of the heavens, riding on a winged bull or in a crescent-shaped boat – in Iraq the new crescent moon sits horizontally in the sky, like a bull's horns

or a boat. Boats used in the region's marshes today still take this crescent form.

Nanna's consort, the reed goddess Ningal, was open to inner knowledge and was an interpreter of dreams. Together they bore the Sun god Utu and his sister Inanna. Utu was god of justice, morality and truth: his symbol was a pruning saw, as well as a form of solar disk (a circle with four triangular points in each of the cardinal directions and four sets of wavy diagonal lines emanating from the circle). Riding across the sky in his chariot, Utu righted wrongs and helped those in distress. At night he judged the dead in the underworld. Inanna (also known as Ishtar in Akkadian or Astarte in Syrian) was a fierce and forceful goddess, linked to sex, war, justice and political power.

Ancient peoples like the Egyptians and Mesopotamians did not distinguish between the physical bodies of the Sun and Moon and the characters of the gods that inhabited them. Persona and embodiment went hand in hand, just like for people and animals. But with the arrival of monotheistic religions like Judaism and Christianity, religious leaders didn't want people worshipping a host of sky gods any more. All-encompassing gods, like the Old Testament's Yahweh, became spirits, disembodied from the wild forces of nature and tied into more managed formal religions. That left celestial bodies themselves open to more scientific forms of questioning.

Equinoxes and eclipses

The ancient Greeks began to distinguish the physical Sun and Moon from the gods linked to them, and to work out many of their properties as we know them today. Their city-states were independent and not ruled by a single king, so

there was lots of room for different ideas. Diverse schools of thought and learning – in mathematics, navigation, engineering and astronomy – sprung up around Greece and surrounding areas, including Anatolia in modern Turkey.

Greek philosophers began to wonder whether physical mechanisms, rather than godly actions, could explain natural processes such as the movements of celestial bodies. The engineer and astronomer Thales of Miletus (born around 620 BCE in western Anatolia) was one early questioner. None of his original writings survives, but according to chroniclers such as Herodotus, writing about a century and a half later, Thales was able to calculate accurately the timings of solstices and equinoxes and the length of the year, having studied geometry in Egypt.

Thales also predicted solar eclipses. He had learnt a lot from the Babylonians, for whom eclipses were a particularly bad omen for the king. The Mesopotamians knew that solar eclipses repeat in patterns every nineteen years (the Saros cycle). When they knew one was coming, they would install a decoy ruler, then dispatch them after the eclipse, when it was deemed safe, and reinstate the original king unscathed. The ancient Chinese also followed eclipses. Around 2000 BCE, it was said, legendary emperor Chung K'ang executed two astronomers for being too drunk to tell him about an impending solar eclipse. They had failed to 'call out the archers nor summon the drummers to frighten away the dragon swallowing the sun'.

Thales famously predicted that an eclipse would occur on 28 May 585 BCE. This happened right on cue, surprising soldiers in the middle of a rumbling war between the Lydians and the Medes, on the plain in front of the ancient city of Pteria (the Anatolian capital of the Medes, near the modern city of Sorgun, about 200km east of Ankara). When

day turned to night, as Thales foretold, both sides nervously put down their weapons. They rushed to sign a peace treaty, cemented by the wedding of a prince and princess from rival sides.

Several times a year another type of eclipse occurs when the Moon falls in Earth's shadow – a 'lunar eclipse'. Illuminated only by light scattered off our planet's atmosphere, the lunar surface darkens and may even appear crimson. To our ancestors, such a 'blood moon' was ominous. Had a mythical creature eaten it? The ancients rang bells or hurled rocks into the sky to chase the animal away. The Mayans and Incas believed that the Moon had been mauled by a jaguar; the Ancient Egyptians that it had been gobbled by a sow. Chinese societies blamed a toad – and worried that famine and disease would follow.

Ancient Greeks wrote of lunar eclipses having different colours, depending on the season and time of day. For instance, the first century CE essayist Plutarch records that 'if the Moon be eclipsed in the evening, she appears dreadfully black', whereas at midnight she emits 'purplish light, and fire'. In the morning 'the blush rises in her face'.

If not gods, though, then what are the Sun and Moon? What are they made of, and how do they and the stars shine? Ancient Greek philosophers began to mull these fundamental questions more than two thousand years ago, setting intellectual wheels in motion for centuries to come.

First, thinkers argued that everything in the Universe must be made from some fundamental substance. Around 600 BCE, Thales argued that it must be water. After all, the presence of seashells within some rocks, like limestone, suggested that they had been formed in the sea. Land clearly formed within silted rivers and estuaries. And mountains gave off mists, which created clouds that made

rain. Rocks, soil, air, everything was connected by different types of water, he concluded.

A century on, other philosophers made bids for other supreme elements. Some favoured air, others fire, or mixtures of water and earth. Anaximander imagined that the ordered world stemmed from combinations of opposites, such as hot and cold, wet and dry, in different proportions. And Empedocles suggested that all substances were made from four key phases: earth, air, fire and water. These elements were held together by 'love' or separated by 'strife', he proposed.

Anaximander imagined that the Sun, Moon and stars were glimpses of fires burning within hollow hoops spinning 'like a chariot wheel' about Earth. Light burst from a small hole in the rim of each wheel, 'like the nozzle of a pair of bellows'. These openings could close, explaining eclipses and the phases of the Moon, he thought.

But Anaxagoras argued that meteorites proved that the whole Universe must be made of stuff similar to Earth. This 'stuff', he proposed, was composed of tiny seeds, like atoms. These seeds join together or break apart to produce the world we see. Thus, the Sun is 'not a god', but a 'hot rock', perhaps a mass of molten metal. The Moon on the other hand is a 'cold rock'. He was on the right track.

Through reasoned arguments like these, the ancient Greeks figured out that the Earth and Moon are spherical, because shadows cast upon the Moon during lunar phases and eclipses were curved. Also, as sailing people, Greeks knew that ships disappeared over the horizon – sometimes with their masts still visible – but could be seen from a higher vantage point.

As travellers, the ancient Greeks also knew that stars appear higher or lower in the sky when you travel north or

south. And as skilled geometers, they were able to use information like this to work out that the Sun was bigger than the Earth, and the Earth bigger than the Moon. They calculated the Moon's distance from Earth to within 10 per cent of the value we know now (384,000 kilometres, or thirty times the radius of the Earth), and that of the Sun to within 50 per cent (150 million kilometres).

All this work required a major shift in thinking from earlier times. Whereas the Mesopotamians and Egyptians were happy to think of the night sky as a canopy or screen, with everything hanging in it at the same distance from us, the geometrically-minded ancient Greeks thought in three dimensions of space.

The heavenly bodies began to be considered as just that, orbs moving through space. But a lot of drama was still being played out on those orbs, in terms of projected human imagination.

Hundreds of years after these advances, 1st century CE Greek scholar Plutarch described the arc of classical thinking about the Moon's face in an essay collected in *Moralia*, or 'customs and mores'. His treatise, written in the style of an intellectual debate amongst philosophers, illustrates in some sense how scientific discussions work. It also reveals how cultural influences seep into otherwise formal considerations of the nature of things. Humans like to back up their beliefs, and our beliefs colour what we see.

Plutarch starts by noting how the dark and light patches that make up the Moon's face appear sharp yet are far from simple. If you look closely, the bright and grey is interwoven in places, or overlain, cut away and compressed.

Thus, the full Moon cannot be a mirror, with its patterns reflections of Earth's oceans – as was one suggestion of those times. Nor can the patches be made of air, for the

Moon is plainly not translucent – it blocks the stars behind and even the Sun during an eclipse.

He also rules out the theory that the Moon is made from fire – there is no glow from embers of coals or flames in the dark-shaded limb, he notes. And what could be burning, he asks? Wood? Fire needs fuel. And in what form of ‘air’ is this conflagration taking place? And anyway, given the Moon is moving, why isn’t a trail of sparks flying out behind it?

Pondering the soft nature of moonlight, Plutarch concludes that it is weak because it is a sort of echo. Sunlight reflected from the Moon ‘comes back to us neither warm, nor brilliant’, just as an echo of a voice sounds fainter than the original cry.

He considers the nature of shadows, asking deep questions that still resonate with philosophers today. Does every light source cast shadows? One philosopher cast in the essay, Posidonius, thinks that stars do not as they are too far away: ‘light does naturally not produce shadow, but destroy it’. Is a shadow a thing in itself? Could it exist within darkness? Apollonides, another speaker, thinks not. Shadows are just unilluminated spaces. Plutarch dismisses such reasoning: shadows surely do cross the heavens, as the phases of the Moon show.

It is these contrasts, Plutarch writes, that lie behind our reverence for the Moon: ‘just as hot things compared with cold seem hotter, and pleasures compared with pains seem more intense, even so bright things contrasted with dark become more conspicuous’.

Plutarch’s arguments step beyond the nature of the Moon to ask how it stays up in the sky and does not fall to Earth. Its motion might keep it aloft, he writes, ‘just as objects placed in slings have a hindrance from falling out in the circular whirling’. The Earth, being heavier, does not move.

But he is unconvinced by the concept of 'gravity', which at the time meant simply that like things attract, which he saw as extravagant. If everything in the Universe is made of the same stuff, wouldn't it all be attracted to Earth and crushed to a point? He teases mathematicians and philosophers who 'choose to defend absurdities by other absurdities' - 'not a wallet-full, but rather a whole juggler's stock and shop-full'.

No, objects must lie in their 'proper' places, dictated by reason, he supposes. By analogy, within the human body, each organ has its place and role. Thus, 'the Sun fills the place of the heart and, like blood and breath, distributes and disperses from out of himself both heat and light'. The Moon must be like the liver or soft intestine, he concludes, diffusing warmth, digesting and purifying.

And what of its purpose? The Moon clearly plays a role in reflecting and diffusing the Sun's light. It must be counteracting the ferocity of the Sun with moisture and coolness, plus acting as a 'rallying-point for the rays of the stars', he writes. Sun, Moon and stars are thus indivisible.

And life? It is possible that the Moon could host life, Plutarch contends, even if it is not visible. Viewed from so great a distance, much of Earth, too, would seem uninhabitable, he notes. Plus, like desert plants, maybe there are roots, seeds and woods that don't require rain and winter but can germinate in hot, dry conditions on the Moon's surface?

And what of the Moon's connection to Earth? Plutarch cites the philosopher Scylla's tripartite view of man: that the Earth is the source of the body, the Moon the soul, and the Sun the mind. Thus, after death the body stays on Earth, the soul rises to the Moon, where it is purified before releasing reason to fly on to the Sun. During an eclipse, souls travel up through the Moon's shadow, wailing and shouting. And

this is why people clatter brass pots and clap their hands to scare away the ghosts.

The Sun in turn creates new souls, and the Earth furnishes them with bodies. And so, Plutarch concludes, the Earth takes back that which she made; the Sun takes nothing; but the Moon both gives and takes, and puts together, and separates. Overall, there is a great recycling of minds, souls and bodies between the Sun, Moon and Earth.

These are profound connections between us and all these bodies indeed. And many of these connections, such as thinking of the Moon as the resting place of souls, persist to this day.

Other Greek philosophers, including Aristotle and Plato, added their own nuances. But generally, by the first few centuries CE, it was accepted in Greece and Rome that moonlight is reflected sunlight, the phases of the Moon and eclipses were understood as the impacts of shadows, and the basic scales of the Earth, Moon and Sun were established.

This knowledge spread over the next thousand years, largely thanks to Islamic astronomers who translated ancient Greek works into Arabic and Latin. But even after all those centuries, the nature of the Moon still niggled. People wanted to get closer still, to pore over its markings and to map it. This was the start of a journey to demystify the Moon, and make it a colonisable commodity.

Seas and spots

In late fifteenth-century Italy, an apprentice to a Florentine sculptor in the Tuscan hill town of Vinci, near Florence, began to learn about nature and engineering. He designed fountains, canals and viaducts, and in 1482 he moved to

become engineer and painter to Ludovico Sforza, duke of Milan.

This designer was Leonardo da Vinci. Amongst his many famous drawings, from fine sketches of the body to proposals for flying machines, are several drawings of the Moon. These are collected in the 'Codex Leicester', a compilation of studies (dated to 1508-10), mainly of patterns of flowing water and hydraulics. (In 1994, the original manuscript was bought by Bill Gates for \$30m, the highest sale price of any book.)

Leonardo was trying to figure out, using the principles of optics, how the Moon shines. Much like the Greeks before him, he began by asking why the Moon is fainter than the Sun. He knew it reflected the Sun's light, and dismissed those who believed that the Moon had light of its own. But, as a sculptor accustomed to working with stone and marble, he wondered too about its texture and contours.

Leonardo asked why, on a clear night when the Moon is a crescent, you can often see the rest of the Moon's disk illuminated very faintly. He reasoned that the Moon must receive light scattered back from Earth, perhaps from its oceans. He sketched the angles of light rays bouncing off the Earth and Moon to explain this 'earthshine'; the Codex includes a beautifully hatched rendering of the circular Moon, part-shaded, part-lit.

On the subject of the Moon's surface, Leonardo ran through a similar train of thought to Plutarch. But he saw things from an artist's perspective: light travels in all directions, but the observer only sees part of the picture, from the point at which they are standing. So, the Moon must be relatively smooth, to reflect sunlight well. Yet, to his sculptor's eye, it did not reflect like very smooth surfaces such as alabaster or crystal. It must be textured, with some

light lost in shadows. His sketches show an exaggerated undulating surface, with light rays bouncing off the crinkles.

As an experienced hydraulic engineer, Leonardo also wondered whether these surface ripples could actually be water waves. As the Moon, like Earth, was its own centre of gravity, water should cling to it too. Ocean waves might then scatter light.

And storms would dim the Moon even more: 'when the sea of the Moon is stirred to tempest by the winds, the waves are larger and the lights less frequent and the enlarged shadows intermingle more with the sparse images of the Sun upon the waves.'

Much of the rest of the Codex goes on to describe and explain other watery features, from the propagation of waves around obstacles to flows through canal locks and weirs, as well as surf, ripples, eddies and whirlpools.

Leonardo's reflections on moonlight, however, did not spread. Perhaps this was because of the secretive way he kept his notes: he wrote them down in mirror-writing, a backwards script, from right to left, only legible if reversed in a mirror.

A century later, the Moon's detail began to be revealed. By 1609, Dutch glassmakers had become so adept that they could make lenses that made a landscape appear several times larger. Another Renaissance Italian, the mathematician Galileo Galilei, heard about these and set about building his own spyglass using spectacle lenses.

By the end of the year Galileo had achieved a magnification of close to twenty (that is, his device made things look twenty times larger than they are). He placed two lenses (one to magnify and another eyepiece to refocus the image) at either end of a 130 centimetre-long wooden tube, held together with copper wire and coated with paper.

This instrument was named the 'telescope' (after the Greek 'tele' (far), and 'scopeo' (I see)).

Galileo turned the tube upwards, towards the Moon. In late 1609 he observed and drew the Moon as it passed through its phases. He published eight drawings in a book, *Sidereus Nuncius* ('Starry Messenger'), which turned him into a celebrity overnight.

Galileo's observations showed that the Moon was not a perfect, smooth ball. As Leonardo and those before him had surmised, its surface was irregular, craggy and pockmarked. In the low light of lunar dusk, the edge of the Moon's shadow (the 'terminator') broke up into light and dark patches, 'like the dark blue eyes in the tail of a peacock' or cracks in a warm glass plunged into cold water.

Rings and arcs appeared, their thickness changing with the angle of the Sun. Bright blemishes broke out on the dark hemisphere, growing and merging with the illuminated flank as the lunar crescent swelled. The spots had a dark edge on the side facing the Sun, and a bright border opposite. 'Just as the shadows of the earthly valleys are diminished as the Sun climbs higher, so those lunar spots lose their darkness as the luminous part grows,' he wrote.

Galileo reasoned why. 'Now on Earth, before sunrise, aren't the peaks of the highest mountains illuminated by the Sun's rays while shadows cover the plain? Doesn't light grow, after a little while, until the middle and larger parts of the same mountains are illuminated, and finally, when the Sun has risen, aren't the illuminations of plains and hills joined together?' The Moon seemed to have mountains and valleys, a lot like the surface of the Earth. He believed, like the ancient Greeks, that the large pale swathes on the Moon's face must be land and the dark zones seas.

Why, then, did the Moon's circumference look smooth and not bumpy like a 'toothed wheel'? The peaks and troughs of many mountains and valleys all stack up, like many water waves on the sea, so that the eye perceives the edge as smooth, he argued. He tried to calculate the height of the mountains, arriving at a figure of several miles, higher than any on Earth.

Galileo considered how the Moon shone, concluding again that it reflected the Sun's rays. This explained why the orb of the Moon still glowed faintly, even on the shaded side, as Leonardo had also noted. Reflected light from Earth accounted for the Moon's coppery tint during a lunar eclipse. 'In an equal and grateful exchange the Earth pays back the Moon with light equal to that which she receives from the Moon almost all the time in the deepest darkness of the night.'

Galileo's ink-wash paintings are not works of art, though they are artistic. Nor are they accurate scientific diagrams, with positions tightly measured. They look like what they were: observant jottings in a notebook, an aide-mémoire to the Moon's nightly appearance. In deft strokes he blends half a dozen shades of grey to bring out the Moon's light and shade and texture. He highlights the mass of the dark ball of the crescent moon against a pale backdrop, or blackens the sky behind to note that the shaded side is not completely dark, but glistens. He captures the grey patchwork of the lunar surface, and outlines side-lit craters and mounds.

But, unknown to him at the time, Galileo wasn't the first person to make a sketch of the Moon seen through a telescope. A few months earlier, on 5 August 1609, Thomas Harriot, a British mathematician and surveyor had used a smaller telescope than Galileo's to observe and record the

Moon's patterning, although his sketch remained unpublished until 1965.

Harriot's pen and ink drawing looked even cruder than Galileo's – he didn't bother shading mountains or craters. But, given his trade, it was more faithful and closer to a map. Harriot had helped British nobleman and explorer Walter Raleigh establish the colony of Virginia in North America. His outlines of lunar features resembled coastlines depicted in maps of the time.

The Sun was another target of the first telescopes. Galileo also published sketches of sunspots, inky stains on the Sun's face. Because the Sun was too bright to look at directly, he projected an image of the Sun through a telescope onto a screen. Galileo wasn't sure what these features were – unlike anything he'd seen on the Moon, these markings moved across the Sun's face. He supposed they must be clouds.

Galileo corresponded about it with the Jesuit astronomer Christoph Scheiner, who observed them too. Scheiner wanted to believe in the purity of the Sun and argued that these spots must be shadows from other planets like Venus orbiting the Sun, rather than flaws. Eventually Galileo convinced him that the spots must be on the Sun's surface or within its atmosphere. They were present when Venus couldn't be in front of the solar disk. Moreover, they appeared ten times smaller than the diameter of Venus.

Sunspot studies continued to be popular until around 1645, but then the spots vanished and interest waned. It wasn't until 1671 that another was found, causing quite a stir. And they remained scarce until 1715. This quiet period of the Sun is now known as the Maunder Minimum, after the astronomers Edward Walter and Annie Russell Maunder, who studied it later in the nineteenth century. We now know that

the Sun follows cycles of activity. Hundreds of sunspots scar its face in a good year, and numbers fall and rise every eleven years. Longer-term cycles lasting decades are superimposed, which account for minima like that in the seventeenth century.

Leonardo and Galileo's considered perceptions of the lunar surface made it something tangible, a place to potentially visit, with features comparable to Earth, such as mountains and seas. The Sun was less habitable, but seeing sunspots hinted at more discoveries. And mapping all these features in far more detail was the path to them.

Charts and globes

Moon-mapping advanced quickly with the telescope. One reason was to assist geographers and surveyors in mapping the Earth. In the seventeenth century, Europeans were busy sailing around the globe colonising other continents. And telescopes were still rarities, gifted to kings and gentry. Leaders and authorities wanted to document their existing and acquired lands. And ships needed to be able to navigate.

Distances north or south of the equator (latitudes) could be measured relatively easily from the peak height of the Sun in the sky – the Sun is highest in the tropics and reaches lower at higher latitudes. But distances around the Earth (longitudes) were harder to pin down. Measuring time differences was one way, by comparing local timings of the same event witnessed at different places. For example, noon occurs later farther west.

But tracking when certain features on the Moon went in and out of shadow during a lunar eclipse offered one method to measure longitude accurately. In 1628 the French

astronomer and priest Pierre Gassendi surveyed features across the Moon to deduce the difference in east-west position between Paris and Aix-en-Provence. Gassendi also produced sketches of the Moon that were far clearer than Galileo or Harriot's crude pictures.

Meanwhile, a wealthy brewer in Danzig (Gdansk in modern Poland), Johannes Hevelius, became obsessed with astronomy and assembled an impressive set of telescopes and instruments at his home. He had all the necessary skills in making astronomical observations, designing and building instruments, and drafting and engraving maps. In 1647, Hevelius published eighteen months' worth of observations of the Moon in a milestone atlas called *Selenographia*.

The stunning book includes three detailed maps of the Moon's entire disk. One displays how it appears in the sky visually, a cartographic version flags its main features, and another labels them. Further engravings show forty lunar phases, as well as observations of sunspots, eclipses, the moons of Jupiter, and fine illustrations of his instruments.

Like the colonial projects emerging in the Americas, this virgin lunar territory needed to be named. And early mappers clashed over what its features should be called. Some wanted to name the most prominent sites after Catholic sovereigns and saints. The pale highlands, or 'terra' (Latin for 'land'), were associated with virtues like dignity, honour and justice.

Hevelius proposed instead that lunar sites should be named after places on Earth, such as sites around the Mediterranean or in classical Greece or Rome. These would be far easier to remember, he thought. Although he cautioned readers not to take this too literally, he got carried away with naming – of continents, seas, islands, bays and even rocks, swamps and marshes.

The system we still use today was an evolution of Hevelius', compiled four decades later by two Italian Jesuit astronomers, Giovanni Batista Riccioli and Francesco Grimaldi, and published in 1651 in Riccioli's compendium on astronomy, the *New Almagest*. Dark 'seas' and light 'plains' were accorded descriptive names, often linked to human health, temperament and the weather. For example, seas were named for crises ('Mare Crisium'), tranquillity ('Mare Tranquillitatis') and serenity ('Mare Serenitatis'). Others were associated with rain ('Mare Imbrium), cloud ('Mare Nubium') and cold ('Mare Frigoris').

Craters were named after scholars and saints associated with astronomy. The names were ordered clockwise in eight zones in order of chronology, with the ancients at the top and more recent ones at the bottom. Related people were clustered together, though Riccioli was clear that his Moon was uninhabited: 'neither do men inhabit the Moon nor do souls migrate there'.

Maps are not the only way to depict the Moon, though. Globes have long been used to envision the world and heavens as a sphere. For example, constellations are etched into the ball carried by the god Atlas in the second-century Roman statue the Farnese Atlas, now in a Naples museum.

Before the fifteenth century, globes of the Earth were made individually and painted by hand. After the printing press, they could be mass-produced. Projections of the shapes of continents and seas could be printed out and cut into slithers to paste on to wooden or papier-mâché spheres.

Such techniques could also be applied to the Moon. In 1661, British mathematician, astronomer and architect Christopher Wren surveyed the Moon and completed the first known globe of its visible surface while professor of astronomy at Oxford University. Wren's lunar globe doesn't

survive, but it was ten inches across, made of pasteboard, moulded in relief and painted.

He designed it to impress the king, Charles II, offering it to him with an inscription which read 'because one world is not enough'. Wren wanted the king to support empirical science – using carefully designed experiments to reveal truths about nature. Instruments like the telescope and microscope could show previously unseen aspects of the world mechanically and thus objectively, beyond the easily confused eyes of man.

The earliest surviving globes of the Moon were produced a century later, and are more artistic than scientific. John Russell, a British painter known for his pastel portraits of King George III and other notables, took a great interest in astronomy. He owned two telescopes and in 1764 began to observe and draw the Moon in earnest. Thirty years later, he pulled all his renderings together and made a lunar globe a foot in diameter. It was as educational tool as well as an object of beauty, mounted on a frame that could simulate the tilt and wobble of the Moon's axis.

Another century on, telescopes were bigger, atlases finer and lunar globes became masterpieces. In Germany, J. F. Julius Schmidt published more than a thousand accurate sketches of the lunar surface in his 1878 atlas. Such detail was wasted on a table-top globe, so Schmidt arranged for a huge plaster-cast model of the visible part of the Moon to be made, nineteen feet across. The vast model was exhibited to great fanfare in Bonn, New York and Chicago; it's now in London's Science Museum.

World globes fed the imagination. They made it easier to imagine long sea journeys to strange lands, rich in spices, timber and silver and ripe for trade. They also made it easier to imagine owning and controlling the whole planet.

Looked at in miniature from afar, the Earth became a toy, an object to possess, touch and manipulate. So did the Moon.

Photographic dawn

Meanwhile, another new tool was emerging. Photographs could capture the Moon's exact portrait, taking away the need for physical sketches – if the complex chemistry and fickle optical techniques could be mastered.

In the 1820s, the first photographers projected light from outdoor panoramas onto plates of glass or metal coated with chemicals that react to light. They focused the rays by passing them first through a lens in a small hole in a screen, protected within a dark box.

It is an old method – the optics of the 'pinhole camera' or 'camera obscura' has been studied since ancient Chinese and Greek times. Experiments with candles and mirrors, the Sun and eclipses showed that beams of light travel in straight lines. A small aperture catches a bundle of light, just as a rowlock holds an oar, to reveal a sharp, inverted image on the screen on which the rays fall. Aristotle, for example, noticed that shining light from the partly eclipsed disk of the Sun through a small gap in his fingers created a bright image of a crescent below.

Leonardo da Vinci read of the camera obscura in the works of eleventh-century Islamic scholar Ibn al-Haytham (also known as Alhazen) on optics. The Italian master produced over 270 diagrams. In 1502 Leonardo documented how it worked: 'If the facade of a building, or a place, or a landscape is illuminated by the Sun and a small hole is drilled in the wall of a room in a building facing this, which is not directly lighted by the Sun, then all objects illuminated

by the Sun will send their images through this aperture and will appear, upside down, on the wall facing the hole.'

The process mimics the eye, he realised, with its opening 'pupil', a lens, and a surface or 'retina' where the image is projected. The narrower the aperture, the sharper the image, but the less light is let through. A balance needs to be struck – a large enough opening to let in light but not so large that the image blurs. Leonardo experimented with different shapes, sizes and numbers of apertures. But chemistry still had to catch up to make it possible to capture the image for posterity.

In the 1820s, French inventor Nicéphore Niépce used a camera obscura to project the view of turrets and scenery from his southern French home onto a pewter plate washed with bitumen. The result, the oldest photograph of nature still in existence, 'View from the window at Le Gras', took at least eight hours to record.

A decade on, more reactive coatings (especially compounds of silver like silver iodide) allowed photos like Niépce's to be taken within minutes rather than hours. French artist Louis Daguerre was one of the most successful commercial developers.

Around the same time, British inventor William Henry Fox Talbot managed to capture 'calotype' images on paper treated with solutions of silver salts. Photography held great promise for the sciences. It was able to produce exact images of nature. François Arago, French astronomer and director of the Paris Observatory, tried to convince the French Academies of its value. Photography was, like the telescope, a new instrument replacing the investigator's eye. It offered a neutral way of seeing the world, without manipulating it. Some scientists took it up. They photographed animals and landscapes and magnified views

down microscopes. But astronomers found it much harder to make use of it.

The Sun was too bright to photograph directly, although its disk might be projected onto a light-sensitive plate to record sunspots. The Moon, on the other hand, was too faint to register; there was no hope for the stars. The Moon's small size in the sky also made it hard to resolve its face. The full Moon is only the width of a thumbnail at arm's length. Increasing the exposure time draws more light, but the Moon's movement would soon blur any image. Magnifying the Moon using a telescope would spread its light over a wider area of the plate. But that would also dilute its impact on the chemicals. Also, the largest telescopes of that time could only see part of the Moon in the eyepiece, not the whole thing.

In 1834 the great French writer Victor Hugo noted his struggle to view the Moon through a telescope at the Paris Observatory, under Arago's guidance: 'this darkness I was looking at began to pale. I distinguished, what? Impossible to say. It was murky, fleeting, impalpable to the eye, so to speak. If nothing had a shape, this would be it.'

Yet in 1839 Daguerre succeeded in capturing a smudge of light from the Moon on one of his photographic plates. He rushed immediately to the bedside of Arago, who was ill, to show him. The image was indistinct, a blur like a comet's tail, according to one report. Nonetheless, German scientist Alexander von Humboldt, who was visiting Paris at the time, wrote of his amazement at this 'portrait of Luna brought forth by herself'.

Unfortunately, Daguerre's pictures of the Moon were destroyed when his laboratory caught fire and burned to the ground on 8 March 1839.

Others persisted. Talbot noted on 15 November 1839 that he had made 'a distinct impression' of the Moon on his paper in ten minutes. And shortly after in 1840, an English-born chemistry professor and physician in New York, John William Draper, succeeded in making a clear daguerreotype of the Moon through a telescope, with an exposure of twenty minutes. Now degraded and blotched with stains, the plate shows the Moon as not quite full, a dark limb sliced off.

Up the coast in Boston, Massachusetts, chemist John Adams Whipple was manufacturing the chemicals needed. He began to make daguerrotypes himself, 'using a sun-glass for a lens, a candle box for a camera, and the handle of a silver spoon as a substitute for a plate'. Whipple had a keen interest in the night sky and began to collaborate with astronomer and clock-maker William Cranch Bond at Harvard College in Cambridge.

After a spectacular comet grabbed public attention in 1843, Bond raised money to build a permanent observatory. He designed it himself to shelter a telescope that was the largest of its kind at the time – a German-built fifteen-inch-diameter Great Refractor, which was installed in 1847. The telescope still sits in its twenty-foot-long mahogany-veneered tube, swinging from an eleven-ton, eleven-foot-high granite block, perched on an even larger granite pier sunk deep into the ground. The observing floor is enclosed in a rotating fourteen-ton, thirty-foot-wide dome made of wood and sheathed in copper.

The scale of the telescope made it hard for an astronomer to look through the eyepiece and Bond designed a special moveable sofa-like chair to sit in. By turning a small wheel, the astronomer could raise or lower the upholstered chair, which is set in a wooden frame positioned with rails and

pulleys. It is still in place, and I was lucky enough to try it during a visit to Harvard College Observatory. The pulleys still run freely, and it's a lot more luxurious a place to sit and observe than at many telescopes I've been to.

Sighting the Moon was the telescope's first task when it opened on 24 June 1847, but photography soon became involved. Over the next few years Whipple and Bond made many exposures at different phases, which they transferred to salted paper prints. In 1850 they also made the first daguerreotype of a star, Vega. The quality of their Moon images was so good they won the prize for technical excellence in photography at the 1851 Crystal Palace Exhibition in London.

Nonetheless, photography had not yet transformed the science of astronomy. Maps of the Moon made by eye still expressed more detail than daguerrotypes. In an 1868 lecture, Berlin astronomer and lunar mapmaker Johann von Mädler poked fun at this slow progress. Daguerre and Arago's promise that the 'unfortunate savants who had spent their lives observing, measuring and drawing' could be retired – or that 'what cost me seven years, the topographic map of the Moon, would be much better made in seven seconds' – had not been met. Yet, he acknowledged, the new technique had its benefits. Photography was superior to drawing, he said, not in terms of capturing natural colours (it did not then) but in how it caught 'shadows and light'.

In 1863, Victor Hugo wrote much more favourably – gushingly even – of a telescope observation of a lunar sunrise. As a beam of sunlight snaked over the surface, Hugo looked on in awe as it picked out craters, escarpments and chasms. He watched as 'immense cones of obscurity were projected, shadows stirred, stripes of rays settled as

would an architrave from one outcrop to the next'. Indeed, 'it existed magnificently', he exclaimed.

It's hard to grasp this elaborate detail in a two-dimensional image, whether printed on flat paper or glued to a globe, however finely illustrated or photographed. As Hugo saw, the Moon's terrain is complicated to comprehend because it is illuminated by the Sun at many different angles, which are always changing. Even vast craters can look like smudges when the Moon is lit face on. Mountains shed long shadows close to the terminator, at lunar dusk or dawn. And dark and light materials on the surface also confuse matters. Is a dark patch just blackish soil, or is it shadowed or roughly textured?

It would take another three decades for the first photographic Moon atlas, published between 1896 and 1910 by Maurice Loewy and Pierre Puiseux of the Paris Observatory. The pair toiled for years to take around 6,000 photos of the Moon over 500 nights to get enough that were sharp. The quality of photographic emulsions (now gelatin-based), glass plates and enlargement and reproduction methods all had to be improved.

What did Moon photographs actually show? How should we decipher lunar geology and geography? One Scottish engineer really wanted to know and, through a keen interest in art and sculpting, developed a way to do it.

Third dimension

From the early 1840s, British engineer James Nasmyth set out to become 'minutely acquainted with the nature and structure of the surface of the Moon'. Turning a telescope at its face was not enough for him. He wanted to depict and understand the moonscape in a more tangible way.

Nasmyth was the son of a Scottish painter, Alexander Nasmyth, who taught him to draw and observe the landscape. But he didn't just want to paint. As a child he made mechanical models, paying his own way through university by selling them to lecturers. He trained as an engineer and went on to invent tools that drove the industrial revolution, including the steam hammer.

Nasmyth liked to be hands-on. He was fascinated by the structures of things and how machines worked. He thought of himself primarily as a 'mechanic', someone dexterous in making as well as able to read and convey forms on paper through drawings. He refused to wear gloves when he worked, believing that the eyes and bare fingers are the keys to engineering. He was intellectual and logical and broke down the designs of his machines into pure geometric forms, such as planes, circles and spheres.

When Nasmyth looked at the lunar landscape, he desperately wanted to know how it would feel to actually be there, to touch it, to experience it up close, with all his senses. And he also wanted to understand how the landscape had formed. What geological processes were at work? He set about trying to replicate it in plaster models.

Shadows were his first strategy for getting to know lunar features, since 'it is mainly by those that their forms are revealed'. He then cast those forms in three dimensions. His mind filled the gaps. The conical sides of many lunar mountains and craters convinced him that they were volcanoes, giant versions of those on Earth.

Nasmyth was familiar with the theories about the Earth's formation that were being developed at the time, including that the Earth had condensed from a cloud of gas and dust around the Sun. British geologist George Scrope and others made the case that many terrestrial rocks, such as basalts,

had their origins in lava spewed from below Earth's surface by volcanoes. Nasmyth reasoned that the Moon might well have formed similarly. As it cooled, the lunar surface would have contracted, he mused, triggering eruptions of molten rock. Lunar craters were the remnants of those volcanoes. He often included a tiny rendering of Italy's Mount Vesuvius on the side of his lunar models, which was widely studied following its eruption in 1822.

Nasmyth's renderings were powerful. His painting of realistic shadows on a two-metre-wide map of the Moon was so evocative that it earned him the Prize Medal at the 1851 Great Exhibition at Crystal Palace in London. As well as Whipple and Bond's daguerreotype, the Moon was the subject of many other exhibits. Designer Charlotte Readhouse showed a lunar globe that emphasised the Moon's 'annular mountains, thrown up like ramparts' around plains of 'alluvial soil' and 'hundreds of cup-shaped valleys dimpling the general surface'. Chemist, astronomy enthusiast and painter Henry Blunt presented a plaster model of the crater Eratosthenes in a hand-held wooden case.

Queen Victoria and Prince Albert were so impressed by Nasmyth's painting that they invited him to dinner. The queen's diary records them looking at his drawings, showing; 'immense volcanic mountains and craters in the Moon' that are 'perfectly round'. Nasmyth's lunar landscapes had 'a perfectly black sky, from the absence of atmosphere, - no vegetation - nothing but the roughest, boldest rocks, and the most intense sunshine'. Victoria was stirred: 'what fields science opens to the human mind!'

Nasmyth's familiarity with the Moon grew, through his hands, eyes and mind. It was a constant process, of looking, drawing, modelling, reviewing and revising, a dialogue more

than just observation. 'The Moon and I are still on the most intimate of terms and he answers me very many authentic questions I put to him,' he wrote.

Like Leonardo da Vinci before him, Nasmyth found natural analogies helpful. He saw links between the great and small, the macrocosm and the microcosm, and reasoned that they might be indicative of similar underlying causes. To him, sunspots mirrored willow leaves. Spiral-shaped nebulae, recently discovered in the night sky, corkscrewed like water does when it disappears down a hole.

Nasmyth was also intrigued by photography, which he referred to as 'the divine solar art' and the 'art of light and darkness'. But he didn't know how to do it. He turned to his friend Joseph Sidebotham, a printer from Manchester, to take photos of his models of lunar craters. Nasmyth's models were pure white, ideal for photography. As 'calotype' expert Talbot put it, photographs of white sculptures are more effective at bringing out forms than drawings or models alone - the shadows can be arranged just so.

In 1874, Nasmyth collaborated with British astronomer James Carpenter to produce a book drawing all his ideas together. *The Moon: Considered as a Planet, a World, and a Satellite* set out Nasmyth's theory for the formation of the Moon and its landscape, from the satellite's condensation from a gas cloud to its cooling, contraction and volcanism. He also explained its spherical shape, size and mass. Dramatic photographs and geological diagrams illustrate the processes at work. Some are superb. High-contrast photos of wrinkles on the back of Nasmyth's hand and a shrivelled apple skin convey a sense beautifully of how the Moon's mountains might have formed.

Nasmyth and Carpenter argue in the book that the visual sharpness of the Moon's surface features must imply that

there is no atmosphere or water present; the 'seas' are merely dark soil. It's a barren world; no life could be sustained there. Although confined to a bird's eye view, they imagine standing on the lunar surface. The scenery 'must be imposing in the extreme, far exceeding in sublime grandeur anything that the Alps or the Himalayas offer'.

It's hard to conjure a vision of what it's like to camp in the fifty-mile-wide hollow of the Copernicus crater, they write, where 'one of our average English counties could be contained within its ramparts'. The authors see specks of colour in the Moon, which is predominantly yellowish-white: the seas somewhat greenish, a few a little ruddy. Bright streaks emanate from some craters as though 'a vast brush charged with a whitish pigment had been drawn over the globe'.

They imagine time passing on the Moon's surface. Lunar days are long – 304 hours from sunrise to sunset, almost thirteen Earth days. There's no rosy dawn or dusk, no blue sky in the absence of an atmosphere. Distances are hard to fathom without haze. Dead silence reigns: 'a thousand cannons might be fired and a thousand drums beaten upon that airless world, but no sound could come from them.'

Daylight erupts like a light switch flicking on: 'from the black horizon the sun suddenly darts his bright untempered beams upon the mountain tops, crowning them with dazzling brilliance.' Night descends just as abruptly.

The stars and planets shine more brilliantly than on Earth, the authors imagine, but the stars don't twinkle when seen through airless space. The constellations appear much the same, but turn on a different celestial axis. Most stunning of all, they write, is the illuminated Earth, traversing the sky and working through its phases as the Moon does for us.

Nasmyth and Carpenter dismiss those who value the Moon simply as a luminary. Moonlight is 'changeable and fugitive' and barely alleviates night's darkness. Instead, they champion the Moon's 'sanitary service'. Humans can get by without the Moon's light, but the tides are vital cleansers. 'While the Sun keeps the atmosphere in constant and healthy circulation through the agency of the winds, the Moon performs an analogous service to the waters of the sea and the rivers that flow into them.' Without its 'aid as a mighty scavenger, our shores, where rivers terminate, would become stagnant deltas of fatal corruption.'

The authors state that with every detail they are 'invoking the conception of things that actually exist; and that we are not, like some imaginary voyagers to the Moon, indulging in mere flights of fancy'. But, as scientists, they also knew that there was much more to learn: the truth plays 'hide and seek' so that 'the dogmas of one era are the exploded errors of the next'.

And indeed, today's scientists know that the Moon formed very differently from how they imagined in the nineteenth century. The beginnings of the whole solar system had been broadly understood. The planets coalesced from small chunks of material in a vast cloud of debris left over from the Sun's formation. More than 4.5 billion years ago this material settled into a disk, like Saturn's rings. Planets and smaller bodies like asteroids began to coalesce. The solar system that we know started to appear.

But soon after Earth formed, it suffered a crash. Another body about the size of Mars, which scientists have named Theia, careened into it. The collision was so massive that nearly all of Earth and Theia melted and merged. A blob of molten magma was spun off and became the Moon. This story explains why the Earth and Moon have very similar,

yet not identical, compositions as well as the Moon's size, distance and orbit. But it took steps to actually get to the Moon and retrieve its rocks to back that theory.

First, Moon-watchers needed to get closer. And that took them to the mountains.

Onwards and upwards

Another scientist who was inspired by Nasmyth's models to look for links between lunar and terrestrial landscapes was Charles Piazzi Smyth, who became Astronomer Royal of Scotland in 1846. Son of a naval officer, Piazzi Smyth trained as an astronomer at the Cape of Good Hope in South Africa, where he observed Halley's Comet and the Great Comet of 1843. As a person, he had much in common with Nasmyth, including a practical bent and artistic skills as a water-colourist.

Piazzi Smyth designed fine bespoke instruments for himself, and he experimented with photography. He specialised in stereoscopic images: two photographs taken from slightly different directions can mimic how the eye senses the third dimension. Focusing on both photographs side by side gives a sense of the real landscape.

He also took award-winning photographs of the spectrum of the Sun, revealing some clues to its chemical composition. If sunlight is sent through a glass prism, it splits into its constituent rainbow colours. But, look closer and dark stripes are also evident – certain wavelengths of light are blacked out. The reason is that cooler gas in the outer regions of the Sun absorbs the light emitted in the hotter inner zones. Different elements within the gas, like hydrogen, oxygen, sodium, magnesium and iron, absorb the

light's energy at certain frequencies. Each chemical element has its own 'fingerprint' of stripes, like a barcode.

It took decades more for astronomers to decipher what elements the Sun is made of from its spectrum. In 1925, Cecilia Payne-Gaposchkin at Harvard College Observatory worked out that the Sun and stars are composed primarily of hydrogen and helium, and are thus quite unlike the Earth. Three-quarters of the Sun's mass is hydrogen; the rest is mainly helium with a smattering of other elements like oxygen, carbon and iron. The Sun shines by fusing atoms together - its furnace turns about 600 million tonnes of hydrogen into helium each second. But sunlight, and moonlight and starlight, must pass through Earth's atmosphere. This contains other elements and molecules like water that also absorb light.

To push his instruments and photography skills to the limits, in 1856, Piazzi Smyth persuaded the British Admiralty to fund him to mount an expedition to Tenerife in the Canary Islands. He wanted to test the proposition, of physicist Isaac Newton in his 1704 book *Opticks*, that views of the night sky were clearer at high altitudes where the atmosphere was thinner.

Newton knew that telescopes could not attain perfect images. Air turbulence always made them a little blurry - astronomers today use the term 'seeing' to describe the sharpness of a star. The remedy for such confusion, Newton wrote, 'is a most serene and quiet air, such as may perhaps be found on the tops of the highest mountains above the grosser clouds'.

Smyth was loaned a yacht and took telescopes, geological and meteorological equipment with him to Tenerife. For two months he, his wife and his team set up camp in the middle of the island, first at Mount Guajara (at an elevation of

2700m) and then at a slightly higher (3300m) site called Altavista. There they recorded the weather and quality of the skies, and proved that Newton was right. High sites were better for astronomy. The stars indeed appeared sharper.

The Moon-like qualities of the local landscape also struck the group, as Piazzzi Smyth recorded in his journal. The whole island of Tenerife is a dormant volcano. Striking views of its main cone, Mount Teide, could be had from Mount Guajara.

Long shadows of the group members as they walked across the high plain, as well as the 'cathedral collection of spires and towers' were, he wrote, comparable 'with those which a telescope reveals in the Moon, at certain periods of its solar illumination.' Piazzzi Smyth photographed these 'lunar rocks' and, on his return, showed them next to a plaster model of Mount Guajara rendered for him by Nasmyth in his presentations.

Thus, Piazzzi Smyth began the habit of astronomers building telescopes at high and dry locations on mountaintops. Astronomers became peripatetic, as they are today, travelling to wherever holds the best views of the cosmos.

The Canary Islands remain one of the best sites for astronomy in the northern hemisphere. Mount Guajara hosts several telescopes, but the Roque de los Muchachos Observatory on the island of La Palma boasts better conditions, and more than a dozen world-class telescopes are now sited there. The Gran Telescopio Canarias, completed in 2007 with a mirror more than 10 metres in diameter, is the largest single-mirror telescope in the world. Another volcano, Hawaii's Mauna Kea, hosts a cluster of thirteen top telescopes, including four with eight-metre-

diameter mirrors. In the Southern hemisphere, parts of the Chilean Andes and Atacama Desert boast even clearer views of the night sky.

Some of these sites are so high that astronomers must battle altitude sickness to go there. Mauna Kea is 4200 metres above sea level, so high that astronomers who work at the summit must ration their time and come down to sleep at lower altitudes. There are numerous tales of observations gone wrong and cars accidentally running off the road when weary scientists' oxygen levels fall too low for them to concentrate.

Astronomers working at altitude are encouraged to write out their instructions before they go, and follow them to the letter. Oxygen-starved brains can't be trusted, they are warned, to make good decisions on the fly. Nights of useful data have been lost by stargazers who decided instead to follow their mental flights of fancy, trying out new ideas or modes of operating that didn't work out so well, as they found out once they returned to base.

And there are cultural issues, too. Piazzi Smyth's legacy of reaching for high, dry sites for astronomy has been good for science. But the practice is not always popular and has historically also piggybacked on colonialism. Hundreds of years ago, most observatories were sited only within major cities and ports, like London, Paris or Boston, where they served governments' timekeeping and navigational needs. While the Spanish government welcomed Piazzi Smyth's visit to Tenerife, and most governments support international observatories within their territories today, mountaintop telescopes are not always wanted.

For example, the use of the summit of Mauna Kea in Hawaii by astronomers is contested. To Indigenous Hawaiians, the mountain holds cultural value as a sacred

space. Building on it is disrespectful and feeds into a long history of inequities in Hawaii, before and after the United States annexed the islands in 1898. A fight has erupted, in particular, over whether astronomers should be allowed to build a new giant telescope on Mauna Kea. At a cost of over one billion dollars the Thirty Meter Telescope – with a mirror 30 metres across, three times wider than the biggest today – would become the largest in the world. But the project has stalled. Each time construction starts, protesters block the road. Mauna Kea Observatory's future remains uncertain, for good or ill.

Other sites have their politics too. Take Antarctica, where nations still vie to build research stations and have a stake in this strategically valuable resource-rich continent. Or Chile, where astronomers have over the years turned a blind eye to dictatorships and revolutions to keep up a watch on the skies. Astronomy has always been an instrument associated with power. And that power has also extended observing platforms beyond the mountains and into space itself.

Apollo missions

The ultimate place for astronomers to get away from the atmosphere is to go into space. And in the mid-twentieth century the race to put real men on the Moon heated up, even if it was for political and military more than scientific reasons, as the culmination of the Cold War space race between the US and USSR. Plenty of other books set out what happened, so I'll skip the detail here. But on Sunday 20 July 1969, Neil Armstrong and Edwin 'Buzz' Aldrin made that first giant leap for mankind.

Only a dozen people have walked on the Moon, actually experiencing what all those scientists, writers, artists, philosophers, poets and dreamers imagined for millennia. Luckily, they brought cameras with them – Hasselblads. Photography was a core part of the Apollo missions, not just for posterity but as a means to provide valuable records for science and humanity alike.

Just as lunar photography pioneers had done before them, the Apollo astronauts captured the vivid light, long shadows, mountains and craters, the grey plains of the Moon. But they added splashes of colour brought from Earth: the red and blue of the American stars and stripes flag, the gold foil of the lander, the rainbow glint of sunlight reflected off a visor.

The words of the Apollo astronauts in later interviews give us a glimpse into what they experienced, and what it meant to them as human beings.

The first flyby of the Moon – on December 24, 1968, during the Apollo 8 mission – resulted in the first photograph of Earth taken from a body elsewhere in the Universe. William Anders' 'Earthrise' picture, showing the blue sphere of our own planet rising above the lunar horizon, is an icon of photography and beloved of environmental movements on Earth.

Anders recalled the mixed emotions of the trip out there. As he sat ready for launch, he anticipated simply flying towards the Moon, seeing it get bigger and bigger, as film-makers like Méliès had portrayed decades ago. Once they got underway, the reality was very different. With the bright Sun sitting just behind the Moon, the astronauts couldn't really see where they were going. Ground control told them not to look in case it damaged their eyes.

As the capsule reached its destination and turned away from the Sun to round the Moon, Anders describes having a 'very eery feeling' as they flew around the far night-side. Out of the windows on one side of the capsule there were so many stars it was hard to tell the constellations. On the other side, 'there was nothing but black - the Moon. It was a bit like falling into a big black hole.'

Then, suddenly, the Sun's rays re-emerged, glancing across the lunar surface at a low angle. 'It looked very desolate, colourless, monotonous, even unfriendly,' Anders recalled. But then the crew got a surprise. The Earth popped up gradually over the lunar horizon - our home planet, the place where we evolved, looking 'colourful, pretty and delicate' compared with the 'rough, rugged, beat-up' lunar surface. The impact was huge: 'it struck everybody that here we'd come 240,000 miles to see the Moon and it was the Earth that was really worth looking at.'

Many Apollo astronauts were keen amateur photographers. John Glenn was the first man to carry a still camera into space - a cheap 35mm rangefinder purchased in a drug store, modified so he could use it with bulky space-suit gloves. On 20 February 1962, on the Mercury 6 mission, he took thirty-eight shots, many of sunsets, which he had always loved: 'I remember sunsets and sunrises ... the way other people may remember seeing a Rembrandt.' From space, there were no dramatic red skies. But the Sun's yellow disk cast rainbows as it plunged behind the veil of Earth's atmosphere. The refracted light was intense, the reds and golds as vivid as a campfire.

Some astronauts knew the technicalities of photography well. Walter Schirra started the Hasselblad trend, insisting on taking his own professional camera with him on a six-

orbit flight in 1962. The bigger, squarer field of 70mm film was better for space photography.

Gordon Cooper, an experienced photographer since he was a boy, nailed the technique. NASA astronaut coach Richard Underwood examined his photographs in detail and instructed the other astronauts in how to use cameras in space. He gave them Hasselblads to play with before they flew and taught them about depth of field, focus and framing.

Recording accurate colours was a problem, however. Camera films are made for lighting on Earth – sunlight filtered through the atmosphere. There's a different colour balance in space. Early photographs of the Moon looked a little too green, so, NASA adjusted the camera settings.

Underwood gave the astronauts lists of photos to take. In early missions these included places of geographical interest or unusual weather systems on Earth. The astronauts liked to gaze down at the planet during their leisure time, which was often when they should be sleeping. So, Underwood gave them 'a list of photography for insomniacs', he recalled. Piloting techniques and manoeuvres were also recorded and the images convey the loneliness of tiny capsules in the emptiness of space.

Photography was central to the whole Apollo program. Landing sites had to be chosen. And bringing back direct images of the lunar surface was a key mission goal. Crews were assigned panoramas and stereoscopic photos to take. They practised in the desert, taking stereo shots by shifting their weight from one foot to the other.

The Apollo missions developed gradually, step by step. Apollo 7 was the first mission in the series to carry a crew into space. The astronauts tested the modules while orbiting Earth 163 times over ten days. Apollo 8 was the first journey

to the Moon itself. It produced historic close shots of the lunar surface as well as Earthrise. Apollo 9 tested systems in Earth orbit. And Apollo 10 was a full dress rehearsal, minus the landing. The spacecraft skimmed to within fourteen kilometres of the lunar surface.

Apollo 11 was the real thing. From the main spacecraft, where he stayed while Armstrong and Aldrin descended in the lander, Michael Collins recorded the lunar module in free flight. He found the Moon's surface a strange place. 'Near local noon time it has a sort of a rosy benign look, and near dawn and dusk it has a monochromatic look - black, grey, not really white.' The look of the terrain varied with the position of the Sun: 'at the low Sun angles of course these craters cast long shadows, and they make the surface of the Moon appear extraordinarily rough, a jumble of craters. You can't imagine that you could possibly land there.'

But only Armstrong carried a camera when he and Aldrin went down. A grainy telecast is the only evidence for Armstrong's steps down the ladder. The shots of a man on the Moon are of Aldrin, not Armstrong.

The lunar module carried a different type of camera, a black-and-white Westinghouse TV camera, adjusted to deal with the high contrast between light and shade on the Moon. The Moon landing was one of the biggest television events in history, reaching 650 million viewers. Armstrong flipped open its case as he eased himself out of the door of the lunar module. The camera sent images and sound back 250,000 kilometres to Earth via an umbrella-shaped transmitter, lined with thirty-eight miles of gold-plated wire, thinner than human hair.

Apollo 12 was the second mission to land on the Moon. Pete Conrad took dramatic panoramas, including elongated shadows of himself and Alan Bean. In one photo a halo of

water vapour envelops Bean's backpack as he strides across the surface.

Bean photographed the 'crescent Earth' and an eclipse of the Sun by the Earth, shedding rainbows. At the peak, he noticed a bright white light in the middle of the Earth moving across the ocean. 'We didn't know what that was. When we got back, Rusty Schweickart pointed out that it was the Moon right behind us reflecting off the Earth' - a reflection just as the ancients had expected to see looking the other way at the lunar 'seas'.

Apollo 15 brought a lunar rover, which the crew bounced around in to explore the Hadley Rille gorge and Apennine foothills. Command module pilot Alfred Worden captured portraits of the astronauts on board, looking at ease in this inhospitable environment. He shot the lunar surface at extremely low-light angles, near sunrise and sunset. Lit from a relatively high 17 degrees, the Sea of Rains looks smooth; from a low 2 degrees its shadows reveal a jagged terrain.

In 1972 Apollo 16 again visited the highlands, where rocks they collected proved that some formations were volcanic in origin. Lunar module pilot Charles Duke - the youngest astronaut to walk on the Moon, at age thirty-six - felt right at home. He took shots of tools, like 'lunar rake leaning against boulder', and brought along a snapshot of his family, which he left behind on the Moon's surface.

Apollo 17 was the last and, at twelve days round-trip, the longest voyage to the Moon. Command module pilot Ronald Evans holds the record for the most time spent in lunar orbit, at 148 hours. Astronauts Eugene Cernan and Harrison Schmitt collected ancient lunar rocks formed when the young Moon had a magnetic field, and 'orange soil' containing volcanic glass. Cernan's photos are some of the most spectacular. In one he managed to get Schmitt, the

American flag, the Earth and the mountains of the Moon in one frame by unclipping the camera and holding it between his legs. Cernan left the last footprint on the Moon.

Scientifically, the Apollo programme proved that the majority of craters were not volcanoes, as had long been imagined by observers on Earth, but were made by impacts. Asteroids and meteorites have regularly crashed into the Moon, particularly within its first billion years, when the solar system was still clearing and rocks ricocheted around. But there was some gentle volcanism early on. Parts of the Moon's interior remained molten and some lava spilled up through cracks in the surface. It flowed fast and cooled quickly, forming plains of fine-grained, dark rocks (basalt) that make up the lunar 'seas'.

After Apollo, manned lunar exploration ceased. Astronauts stayed within Earth orbit, aboard Skylab, Mir and the space shuttle. But photographs taken from space were not as clear. Thicker windows and increasing air pollution shielded views of Earth and the stars. The lunar surface stayed unwatched.

Yet Neil Armstrong's small step wasn't only a technical feat; it was a great cultural bound. It crossed a threshold – between reality and imagination.

The *New York Times*' special issue the day after Armstrong's landing was packed with detailed descriptions and diagrams of how the ambitious project was pulled off. Pages gushed with positive plaudits from world leaders and thinkers. But the verses poets had been commissioned to write stood out – as almost uniformly sad. For them, Armstrong's boots on the Moon's face weren't so much a triumph as an attack on their muse.

Poets rebel

Gone was the poets' Moon of desire. Once humans had touched it, the heavenly playground of gods was an empty anachronism. Far from celebratory poems printed in the *New York Times* cried out that the 'strange white goddess' was 'imprisoned in her ash'. No souls of the dead clung to this 'chassis orbiting about the Earth'. The Moon was a mere 'cold thing in the Universe'; Armstrong and Buzz Aldrin were merely 'heroes who sift silver for its dust'.

Perhaps this reaction was all too human. Just as real relationships can sour when we realise our lover's imperfections, our affair with the Moon has often chilled as we learned more about her.

Apollo astronaut Alan Bean recognised that the program didn't emphasise the human aspect enough. 'We didn't take too many tourist photographs' or show 'people doing a lot of the fun stuff we did on the Moon,' he said.

Eugene Cernan found it hard to convey the full experience of being there. The pictures helped show where they had been but 'they don't properly record the emotional or the spiritual part of the history that took place'.

Each astronaut came back with a different description of what the Moon was like. Some of them, like Frank Borman, saw just shades of grey. Others perceived colours – Al Worden experienced shades of brown. NASA tweaked the prints to match what each astronaut recalled seeing. Bean became an artist on his return, painting rainbows from his imagination into the Moon's steely landscapes.

And the astronauts were characteristically modest about what they'd achieved. Cernan found the journey enriching; it had changed him, he said. He felt 'the luckiest guy in the world' to have gone. But he still had to face reality and get

on with life on his return. Ronald Evans saw it mainly as a point of national pride: 'We as Americans did not conquer the Moon, because that was not our aim. But the American flag is up there, and we proved to the rest of the world that our nation could do that.'

But the Moon's allure is still there. As well as China's Chang'e missions, India and Japan have sent probes to the Moon in recent years. NASA and the European Space Agency (ESA) are seriously contemplating building an outpost there. A vision supported by US presidents, the lunar base would serve science, commerce and be a technical stepping-stone for sending astronauts deeper into space, to asteroids or Mars.

ESA's vision is for a collective 'moon village', open to anyone who would like to live off-planet and who can bring skills and tools to share with a growing community. It sounds politically utopian and democratic, much like a lunar version of the European Union ideal. ESA's efforts so far have been mainly conceptual. The agency is not preparing particular plans for buildings but is developing processes that might usefully be rolled out on the Moon. Shelters and tools might be 3D-printed from lunar soil, or homes inflated to reduce the need for materials.

America's dream is more of a managed 'gold rush'. Governments and companies would jointly set up mining operations and settlements. If the political will is there, NASA claims that a small base could be built for as little as ten billion dollars within a decade.

Scientists would probably be amongst the first lunar settlers. The Moon's far side is an ideal place for a radio telescope that could peer deep into space without being swamped by electronic interference from Earth. Resources

on the surface could be assessed, from reservoirs of water ice that could support the lunar base to rare elements.

Fifty years from now, the Moon might look very different. While we have grown accustomed to the steady stream of satellites glinting as they roll hurriedly across the sky, would we accept the desecration of the Moon, no longer a clean crescent but a glitzy atoll in the black cosmic ocean?

And what of the Sun? While our increasing demand for solar power should make us care more, climate change doesn't sit well with her either. Plans to post giant mirrors in space to reflect sunlight to slow the pace of global warming, or to light cities after dark, could also destroy our natural view of the night sky. Sulphate particles lofted into the stratosphere to act as a temporary sunblock might make the air cooler to combat the effects of rising carbon-dioxide levels, but the consequences are unknown and might include damage to the ozone layer and changes in regional rainfall.

If the Moon becomes just another industrial site, and the Sun too hot for our comfort, poets would have to find new metaphors. No longer heralds of truth and justice, romance and longing, the inhabited Moon and shaded Sun would instead become yet more depressing exemplars of human excesses rather than symbols of unity, peace and love.

It's not far-fetched. In the words of Neil Armstrong, 'we're required to do these things just as salmon swim upstream.'

As companies begin to privatise space travel, the Moon is already in their sights. One commercial proposal to deposit the cremated ashes of people on the lunar surface, for a fee, has led to some outcry. The Navajo Nation, on behalf of all Indigenous Peoples, has called for the Moon to be treated with greater respect, owing to its wide cultural significance. Many people around the world, me included, would wholly

agree. Why should we lose it to developers, when it means and has meant so much to so many? The Earth must speak up for the Moon.

2

Worlds

Planets and Life

Urge to explore

Curiosity, Spirit, Opportunity, Sojourner. Those are the plucky names of NASA rovers that have explored the surface of Mars. They mirror admirable human qualities, as US schoolboy Alex Mather, from Springfield, Virginia, noted in his winning essay in a NASA competition to name Perseverance, the latest rover in this set, which reached Mars in 2021.

In his essay, Mather outlined how he saw exploration as a key driver for humanity. Given the resilience of the human race, the schoolboy saw no reason why people could not set foot on Mars one day. 'Humans evolved as creatures who could learn to adapt to any situation, no matter how harsh,' he wrote. 'We are a species of explorers.' People will meet many setbacks on the way to Mars but never give up. 'The human race will always persevere.' Bold words indeed.

But why do we *want* to go to Mars so much? Why has this planet, in particular, become a key goal for space agencies

and billionaire rocketeers? Even a return to the Moon is viewed today as a stepping-stone for a longer crewed mission to Mars decades from now. The red planet has certainly taken a hold on our imaginations. And again, age-old stories and quests for knowledge lie behind our obsessions.

While seeking to know Mars better, and the other planets, we've come to understand our solar system – from how the planets are ordered and move within it, to its scale and something of its origins. Future missions and observations might well give us glimpses of how life on Earth might have started and whether it is common or rare elsewhere in the Universe. But, even with all this progress, we are still asking the questions which astronomers and philosophers have asked across the ages.

Culture has also influenced how astronomers have comprehended the science of planets. Searches for life on other planets have gone on in various ways for hundreds of years, and have spilled into the imaginations of the public, journalists and writers. Just as explorers on Earth have long surveilled new lands to control, from remote islands to high mountains and distant continents, Mars is the latest outpost marked for conquest. Its exploration has more than scientific intent.

Much as the Moon's patterning suggested mountains and seas where humans might feel at home, geologists' view of Mars shows that it is also rich in seemingly familiar landforms. And in some ways it might be even more Earth-like than the Moon: satellite images reveal crater rims encrusted with carbonate rocks, much like limestones. On Earth, the carbonates within limestones settled out of water in which they were dissolved, slowly encasing dying organisms as fossils within them. Such rocks host some of

the oldest known evidence for life on Earth, including fossilised mats of bacteria known as stromatolites. The oldest examples, found in Western Australia, date back 3.5 billion years. Geologists eagerly anticipate unlocking the Martian equivalents, if they exist, to see whether they can spot signs that microbes or other organisms were also once present, or whether Mars never hosted life and Earth is unique in doing so.

Such profound questions – over similarities of another world to Earth, potential habitability for humans and the origin of life – have attracted dozens of unmanned missions to Mars from many nations over the years. Political considerations have, too, as having access to deep space is a signal of a nation's power and technological prowess. The Moon is already conquered, and has become a playground already for many states' orbiters and landers. Mars is every serious spacefaring nation's next top destination. And landing anything on it is still quite a prize.

A slew of successful missions in recent years has made going to Mars look routine. But it is anything but. The journey is one thousand times longer than to the Moon and far riskier. The red planet has twice the surface gravity of the Moon and a thin yet stormy atmosphere which makes it hard to land without being blown off course. A heavy bump on a surface littered with sharp boulders and rocks can take its toll. More than half of missions to Mars have failed for some reason, from using incorrect units in calculations to faulty radios, erroneous commands, misfiring rocket boosters and fuel leaks. The prize is great but challenging to win.

Of all the planets, Mars has been most alluring, the one that has driven our urge to investigate them more. Its brash ruddy colour, its quirky motions across the sky and

tantalising features have caught our attention and imaginations. And it's opened a window onto the rest of the solar system and to big questions, such as the origin of life. But as our investigations have proceeded, we've come to some startling fresh discoveries. Life's origins might not just require a warm little pool or seashore on a rocky planet much like Earth. It might emerge in far stranger places, such as the icy moons of Jupiter and Saturn.

Past obsessions

It's only been sixty or so years since human-made craft first travelled to view and touch Mars. But our obsession with the red planet is millennia long. At times it has even surpassed our level of interest today, with epidemics of what is often dubbed 'Mars fever' breaking out. People's urge to learn more about this charismatic planet has been an impetus for many discoveries about our solar system, from the relative positions of Earth and the Sun to the order and scales of planetary orbits, theories of the origin of life, and searches for it.

Thousands of years ago, the red hue of Mars certainly caught the eye of the ancients. Many cultures linked the crimson planet to blood and heat. East Asian cultures know Mars as the 'fire star', emblematic of that element. Others gave it a human character, and a fierce personality to boot.

In Western tradition, the planet is named after the ancient Roman god of war, who is associated with rage, warriors, masculinity and youth, as well as being a bringer of pestilence and destruction – qualities that would make you stand up and take note. Ancient Rome's Mars had much in common with the Babylonian god Nergal, ruler of the underworld, who was also linked to fighting, disease and

storms. The ancient Greeks made similar links to their war god, Ares.

The Indian Vedic text 'Brihat Parashara Hora Shastra', composed in the mid-first millennium BCE, describes Mars as having blood-red eyes, being fickle-minded, liberal, bilious and given to anger. Arab texts describe celestial Mars as 'the blind lord', who strikes out indiscriminately in his rage. Societies around the world that have prized warrior skills, including Ancient Greek, Pawnee, Toba, Māori, Australian Aboriginal, Celtic, Germanic and Indian cultures, have looked to the red planet as a source of 'martial' or military power. And for much of history the word 'Martial' was widely used rather than 'Martian' – it's only recently that we've tended to the latter as a more neutral term for the planet itself.

Like all planets, Mars is a wanderer in the sky – the word 'planet' comes from the Greek word 'planetes' meaning wanderer. It moves silently amongst the stars, shifting a little in position against the backdrop each night. Perhaps that's why the ancient Sumerians called planets 'wild sheep'.

Each night, Mars moves a little farther east. And every couple of years, if you were to plot these points, you would catch it doing something surprising. It seems to stop and reverse its path through the constellations, stepping a little west before stopping and pursuing its eastwards journey again. This backward looping motion is said to be 'retrograde'.

We know the reason now. Earth laps the Sun twice for every single orbit Mars makes. It's like two cyclists on a racing track, where the one in the inside lane is travelling faster. Mars seems to fall back as we pass by it. Because the orbits of Earth and Mars aren't quite in the same plane, and

Mars's orbit is more oval than Earth's, Mars also appears to shift a little up and down in the sky. Thus, these retrograde events mark out a loop or zigzag on the sky. It's the same for all planets farther away from the Sun than us.

But long ago, ancient astronomers were flummoxed by this odd behaviour. Finding strange regularities like this, on top of the cycles of the Moon and Sun, probably spurred them to keep a firmer eye on the heavens. Tomb paintings suggest that as early as 1500 BCE, ancient Egyptian astronomers had noticed Mars's odd reversals. Some scholars think Mars's absence from the celestial line-up in the ceiling paintings of Senenmut's tomb at Deir el-Bahri, for instance, stems from the planet being retrograde when it was painted – perhaps too bad an omen to show over someone's death bed.

The ancient Babylonians were fascinated by the movements of these special celestial bodies that wandered amongst the stars. They set about trying to map the positions of the five visible planets accurately, probably using just the naked eye and a simple clock regulated by flowing water to tell the time. They worked out the number of years between a planet returning to the exact same point on the sky and recognised that the heavens are periodic, with repeating cycles that differ for each planet: they couldn't understand why this was, but they were able to track the patterns anyway. They even used them to run their society.

Archaeologists have unearthed many astronomical texts from ancient Babylon, some from excavations of sites of ancient cities and libraries, some passed on by traders and dealers who obtained them from more informal finds. One set, known as the Astronomical Diaries, contains daily observations of the Sun, Moon, stars and planets, which

were monitored much as we track the weather. Most of these diaries date from 750 BCE to 75 CE and were written by scribes in cuneiform script on clay tablets. These records are invaluable to historians as they can date many of them to the day from the detailed information provided on the Moon. That we have daily records of so much and such detailed information spanning six centuries is still remarkable.

Each astronomical diary spans one month. It opens with an observation of the new moon – a slender crescent – and comments upon it, such as whether it was high or low in the sky and the length of time from sunset to moonset (the Babylonian day was split into 360 segments of four minutes). The diaries then chart the motion of the Moon relative to thirty or so key stars and the planets, including distances between them and height above the horizon. There are remarks about the visibility of the full moon and any eclipses seen. And there are also comments on the planets, weather and unusual meteorological conditions such as rainbows.

Zodiacal signs hosting the planets were recorded, as was the height of water in the River Euphrates. Newsworthy events were logged, such as a fire or theft. Unfavourable weather was noted, and it was often so: these ancient astronomers recorded night after night of clouds and rain, mist, fog, hail, thunder, lightning and high winds. Perhaps this surly weather is one reason why the Babylonians became so good at mathematics – to fill in the gaps with estimations when observations weren't possible, which was quite a lot of the time.

The diaries also record economic information – about the costs of various supplies, such as barley, dates and wool. Fast-changing prices were flagged with finer details, such as

costs rising in the morning, at noon and in the afternoon. Celestial rhythms were well and truly lashed to the whole economy and running of this society.

And the Babylonians went further. They analysed all this information to make predictions about what would happen in the future. They asked what was likely to happen when a planet returned to the same spot – every eight years for Venus, for example. Omens could also be derived. For example: ‘if Jupiter approaches and stands where the Sun shines forth ... barley and sesame will increase.’ Or, ‘if Mars comes close to the [constellation of] the Fish, production of fish will disappear from the land.’ Rituals were deployed to stave off the worst, or to keep prices stable.

The retrograde motions of Mars were remarked upon specifically in these notices. One letter from the king’s scribe to the king’s personal scholar queries the movements of Mars to clarify what omen he should tell the king. Was Mars, retrograde, entering the constellation of Scorpius, or the head of Leo, he pleaded? Precise meanings mattered. The former, and the king should not venture outdoors; the second, and his reign would end. Mess it up, and it could be career-ending for the scribe.

The Babylonian scholars that worked on these diaries were a small elite group. Errors and quirks in the logs indicate that they weren’t official published texts as such, more like personal logs. At the time, predictions and omens were kept secret as they were seen as the domain only of the king and experts. The ‘uninformed’ could not see the crucial celestial numbers, which issued from the realm of the gods.

Over the centuries, ordinary people increasingly wanted access to such information too. And later Babylonians did go on to develop a system for personal horoscopes, whose use

spread to Greece and beyond, and form a basis for the ones we know today. Babylonian astronomers also gave us our divisions of angles and time. They used a sexagesimal number system, based on multiples of sixty rather than the multiples of ten we use today. It's the origin of sixty seconds in a minute and sixty minutes in an hour or 360 degrees in a circle. It was useful for writing and evaluating fractions and for performing mathematical calculations.

Babylonian mathematicians developed forms of algebra that were a big help to astronomers in making even more accurate predictions. And the Astronomical Diaries tablets also set out equations for calculating the behaviours of a planet, such as forecasting when it would rise or set in a month's time, for example.

Historians don't have much evidence on how Babylonian astronomers thought about the nature of the planets they tracked, or how the whole celestial sky fitted together, but it seems as if they came at it from a largely pragmatic point of view. Did they ask themselves what Mars was? Or how far away it was? Did they wonder about the deeper meaning of these heavenly cycles? Given their mathematical prowess, which would have enabled them to frame such question, perhaps they did. But as far as we know, they viewed the night sky as a two-dimensional display. Their thinking was quite unlike how we consider the solar system and stars today, as stretching out across three dimensions.

Nor, apparently, did the Babylonians think in terms of the planets as objects moving in time. Each return to a given position or state was essentially the same, to them. Babylonian astronomers logged in their diaries only key positions that were most important to know, and made predictions about when a planet would be in such or such notable position again.

They didn't conceive of 'orbits' as such, and their algorithms have no parameters that we would think of as physical in origin, like force or mass. Their calculations were arithmetic, centred on manipulating numbers, through adding, subtracting, multiplying and dividing. Their approach was more like an early computer code than a physical theory. In a nutshell, Babylonian astronomy was incredibly useful but it wasn't profound.

Nonetheless, Babylonian timetables for the planets filtered through to astronomers across the Near East. Historians know little about how they were shared, although it seems that astronomers at that time travelled widely to learn from and speak with others about key problems. In any case, the same question plagued them all - why did planets like Mars show retrograde motion? And accounting for this peculiarity became the key to unlocking understanding about how all planets move and the nature of our solar system.

Melting pots

For more than a thousand years, astronomers all around the world sought to find an accurate mathematical description of the motions of the planets. Some did so out of curiosity, others to serve powerful leaders. But it's fair to say that during this period the mingling of different cultures reinforced and spread knowledge markedly, with the most adept astronomers training others, notably in ancient Greece, the Middle East, Central Asia and China.

At the heart of these endeavours was the ancient Greek philosophical concept that the planets must move along perfect circular paths. Perfect geometrical shapes were held in high regard, and only these ideal shapes were believed to

be worthy of cosmic mechanics. For example, in the fourth century BCE, the natural philosopher Aristotle imagined that the Moon, Sun, planets and stars were fixed to spheres of some substance that rotated around Earth. Early mathematicians struggled to make this explanation fit exactly what they saw on the sky, though, leading to ever more sophisticated adjustments to their ideas.

Mathematical descriptions of planetary motions became so complex that only the world's most expert astronomers could handle them. The Greek mathematician and philosopher Eudoxus sought to explain the reversals of planets like Mars using principles of geometry – the mathematics of points, lines surfaces and solids. He considered a planet as a dot on the surface of a sphere that was free to rotate against a fixed backdrop. The spinning of the sphere might explain Mars' motion across the sky, he reasoned. And, if someone was watching it themselves from another sphere that was spinning in the opposite direction, then they might well see it sometimes seem to stand still.

It was a nice idea, and the general concept that planets move relative to one another on a roughly circular basis was headed in the right direction. But the details didn't match what Mars actually did – carving out a figure of eight or Z-like wiggle in the sky over many nights. And it couldn't explain how often Mars went retrograde or why it took as long as three decades to return to the same point in the sky.

So the Greeks added more rotating spheres to the mix, hoping that some three-dimensional mechanism made from an intricate series of 'cog wheels' could account for finer details. For instance, imagine that the dot-like planet isn't just sitting inertly on the surface of the spinning sphere, but it is *also* circling about that point, whipping round and

around the surface of a smaller sphere as the larger one turns. That might add in an S-like curve to the planet's path.

These small extra circles were called 'epicycles'. The origins of such models are obscure, written on papyrus documents that are mostly now lost. But one notable account was given and refined by Ptolemy, a polymath who lived in Roman-run Alexandria (in what is now Egypt) around 150 CE. Ptolemy was a prolific writer and scholar who produced treatises in astronomy and astrology, geography and even music. His most famous work, titled *The Mathematical Systematic Treatise*, is better known now as the *Almagest* - stemming from an Arabic word 'al-majisti' for 'the greatest' treatise. It spans thirteen chapters, of which the last five concern the planets.

In the *Almagest*, Ptolemy refined earlier models of epicycles until they described planetary motions reasonably well. His great advance was to take measurements not from the centre of the large sphere but from a point slightly offset from it. Adding in a few extra wobbles made it easier to reflect the planets' real motions on the sky, slowing or speeding up slightly, for example.

Ptolemy went on to estimate how far away each planet was from Earth relatively, based on how long it took them to traverse the sky. And later he added approximate distances, which are far from what we now know but only by factors of one hundred or so: not bad when we're dealing with many millions of kilometres. After the Moon, Ptolemy believed, came Mercury, Venus, the Sun, Mars, Jupiter, Saturn - and finally the outer shell of stars. Relative to our planet, that's not a bad job. Relative to the Babylonians' limited pattern predictions, Ptolemy also changed the question to one that we can still ask today: given the time, where is a given

planet? And he included in the *Almagest* tables for providing an answer.

The *Almagest* was a landmark work that astronomers would consult and try to tweak for centuries afterwards. Byzantine scribes transposed it from papyrus onto more long-lived parchment. Copies and translations were made and distributed via the Islamic world and then medieval and Renaissance Europe. Islamic astronomers made further refinements, including adjustments to accommodate the Sun's path, for example, owing to what we now know is the slow wobble of Earth on its axis.

One major centre for such work was Maragheh observatory in northwestern Iran. It was established in 1259 CE under the directorship of Nasir al-Din al-Tusi, a prolific Persian scientist and astronomer. Tusi wrote astronomical handbooks detailing the motions of the planets and cataloguing stars, including *Zij-i ilkhani* (the 'Ilkhanic Tables'), which is based on twelve years of observations. He was an expert in trigonometry and developed the mathematics of sines and cosines and tangents beyond astronomy.

Tusi managed all this despite living in troubled times and facing personal peril. His story illustrates how important astronomers were at the time to powerful leaders, as only they could plot the intricate workings of the heavens.

Tusi was born in 1201 in Tus, near Meshed in northeastern Iran, at a time when Central Asia was in turmoil as the Mongols, led by Genghis Khan, swept through conquering and massacring. When the Mongols reached the Tus area in 1220, Tusi sought refuge in the mountains.

That is, until 1256, when the castle in which Tusi was living was attacked and destroyed by another Mongol leader, Hulegu, a grandson of Genghis Khan. Luckily for Tusi,

Hulegu was fascinated by science and took the astronomer under his wing as a scientific advisor. Historians question to what degree Tusi chose to take the Mongols' side, or whether he had to work with them to stay alive. But, in any case, Tusi was at Hulegu's side when the leader successfully invaded Baghdad in 1258.

Pleased with how well his conquest had gone, Hulegu agreed to construct a fine observatory for his aide at his new capital of Maragheh. Traces of its walls remain today. The site held some of the finest astronomical instruments of its day, including a four-metre-high quadrant for measuring the precise angle of stars and planets above the horizon, as well as a fine library.

Maragheh became an important hub for astronomers from all over the world. Under one roof, pupils could learn about many aspects of the discipline from different tutors. Knowledge was widely shared. Astronomers from all backgrounds, even slaves and foreigners, could rise up the ranks – as long as they served their Mongol patrons well. The consequences of making a mistake were dire, though. Another astronomer, Husam al-Din, who tried to dissuade Hulegu from attacking Baghdad, was executed after that invasion succeeded.

Scholars from as far afield as China, Tibet and India worked at Maragheh. They came from across the Mongol empire, which stretched from Hungary to Korea. Why were the Mongols so keen on astronomy? They believed their military success was down to the will of their primary god, Tengri, the deity of the heavens who created the Universe. Tengri was infinite and timeless. Mongolian rulers knew they owed their position to the grace of Tengri, not their bravery and strength. And they hired astronomers to try to fathom

his divine wishes. If a leader fell short of Tengri's expectations, they would be brought down.

Mongol leaders consulted astronomers about everything, from when to put a king on the throne or take a medicine to what the stars had in store for a prince on his birth. Genghis Khan brought the astronomer Yelü Chucai with him on his campaigns – Chucai was from the Khitan people, nomads from northeastern Asia. Möngke, Genghis's successor, imagined setting up an observatory staffed by Muslim astronomers. But it fell to his younger brothers to realise that, and more.

When Möngke Khan died in 1259 he left no successor. His brothers and cousins squabbled over who would become the new khan. Civil war broke out, and the vast empire split into four regions. Hulegu ran the Ilkhanate, in Southwest Asia, where he built the Maragheh observatory. His brother Kublai took over in China. Other family members secured the rest.

The Chinese too were well advanced in astronomy. Emperors there also used celestial motions, rhythms and omens to manage their state. To win heavenly approval, it was essential that each emperor had an accurate calendar for tracking and predicting celestial events, and that such vital knowledge stayed within the elite court.

Kublai Khan, settling in as the new ruler of China, adopted this system and made reforms. He recruited and registered astronomers from across China, sent them to schools and institutions to train, and thus assembled a coterie of experts able to produce an accurate calendar. He forbade others from making calendars or interpreting omens. His 'granting the seasons' program lasted for 360 years.

Astronomers from outside China were included, sometimes involuntarily. When the Mongol elites conquered a land, they captured local astronomers and brought in

others. They made them work for them, their families and contacts, and considered the experts their personal property.

In China, the court was very bureaucratic. In 1271 Kublai established an office for non-Chinese astronomers, the Muslim Directorate of Astronomy, alongside the existing Chinese Directorate of Astronomy. Kublai also set up an Astrological Commission to produce the calendars. The first director of the Muslim directorate, Jamal al-Din, had worked for Kublai for decades and brought Islamic map-making methods to China. Kublai's astronomer Liu Bingzhong was the core figure in the Yuan court.

Thus, for a while, Muslim astronomers worked closely alongside Chinese ones, albeit in parallel tracks and with some rivalry.

Some Muslim astronomers spoke no Chinese. Islamic scientists took little from China. And the Mongols didn't adopt the Chinese calendars that Kublai facilitated. Yet Mongol patronage kept many systems going simultaneously.

During this period, people and texts moved widely and much knowledge was exchanged. This consolidation of astronomical ideas and observations would gradually overturn and challenge everything that was previously thought about our place in the Universe.

Displacing Earth

Scholarly connections kept Islamic, Chinese, Greek and ancient astronomers' know-how circulating and slowly advancing. And in the fifteenth century, European astronomers, too, began to grapple with the intricacies of Islamic scholars' works and to unravel the geometry of the solar system. As observations of the planets' motions

improved, a series of fresh interpretations, colourful characters and some haphazard events brought us largely to the solar system we know now, with the Sun at the centre and planets orbiting around it.

One notable figure was Polish astronomer Nicolaus Copernicus, who was born in 1473 in the city of Torún, in the north of the country. Copernicus's father's house in the old town – a tall gothic townhouse with grand windows and brickwork – is now a museum to his famous son.

Copernicus studied mathematics, astronomy, geography and philosophy at the University of Kraków. His courses introduced him to Greek descriptions of the Universe, with a view to being able to make calendars to follow holy days, to calculate horoscopes and to navigate at sea. One of the old texts Copernicus read was *Tractatus de Sphaera*, written in 1220 by Johannes de Sacrobosco, an Oxford-educated English scholar who used Arabic methods of arithmetic and algebra. This book was the main teaching text in astronomy in Europe at the time and remained so until the seventeenth century. It set Earth at the centre of a spherical Universe, described the rising and setting of celestial bodies as seen from different locations, and Ptolemy's theory of the planets and eclipses.

Copernicus then trained in Italy to become a church canon, a post he took up at Frauenburg in 1497. This role gave him a comfortable income and time to pursue his learning and he set up an observatory there. At Bologna, Rome and Padua, he expanded his knowledge of astronomy, as well as medicine. At the time, physicians made use of astrology for explaining ailments.

In 1514, Copernicus distributed a small hand-written booklet, called the *Little Commentary*. It might be a modest name but the ideas in it were huge. This work set out his

bold premise that the centre of the Universe is actually near the Sun, not the Earth. Copernicus wrote that the stars are much farther away than the Sun, that Earth's rotation is why the stars appear to move on the sky, and that cycles of the position of the Sun stemmed from Earth revolving around it.

And, finally, he surmised that the retrograde motions of the planets were caused by the motion of the Earth, from where we observe them. This last point in particular was remarkable. Earlier scholars had suggested many of these things, but none had (as far as we know) put everything together.

Copernicus immediately started working on a far bigger text, which included all the mathematics. Given what was at stake, Copernicus wanted to make sure to get everything right before he published it. He spent the rest of his life developing his monumental work, titled *De Revolutionibus*. It was finally published in 1543, apparently at the behest of a young colleague, Georg Joachim Rheticus, who pleaded with him to release it to share his ideas fully with the world.

In the book, Copernicus set out his reasoning: 'At the middle of all things lies the Sun. As the location of this luminary in the cosmos, that most beautiful temple, would there be any other place or any better place than the centre, from which it can light up everything at the same time? Hence the Sun is not inappropriately called by some the lamp of the Universe, by others its mind, and by others its ruler.'

Rheticus himself penned an introduction to Copernicus's work, in which he described how Copernicus worked objectively and meticulously, by setting out observations of all ages alongside one another and looking for where they conflicted. It was Rheticus who took Copernicus's 200-page manuscript to a printer in Nuremberg. But he couldn't stay

to see the process through, and asked a theologian with experience of printing mathematical texts, Andreas Osiander, to oversee it. But Osiander added a twist.

Osiander replaced Copernicus's preface with a 'letter to the reader', written by Osiander, which played down the repercussions of putting the Sun at the centre of the Universe, which were counter to prevailing beliefs and religious doctrine at the time. Putting the Sun at the heart of the cosmos displaced humans, and thus God, from being pre-eminent. It contradicted the church's official view, based on ancient Greek ideas and Ptolemy's model, that all celestial bodies circled Earth: decades later Galileo was put on trial and placed under house arrest for heresy for backing Copernicus's Sun-centric view. To protect Copernicus, Osiander wrote that the book did not claim this arrangement as the truth, but merely as a means of improving the accuracy of calculating the planets' motions. Rheticus was appalled. But others think this intervention might have ensured that the book was read and not ignored or banned.

Copernicus's great work had its limitations. Like Ptolemy, he still assumed that celestial bodies moved in circles. He still used epicycles to finesse the details. For centuries hence, many astronomers considered the book just another implausible hypothesis, one in a long line since Ptolemy. Copernicus expected detractors. His original preface noted as much, adding 'I disregard them even to the extent as despising their criticism as unfounded.' But alas, Copernicus couldn't correct Osiander's act of deception. He only received a copy of the book on his deathbed.

A few years later, a Danish aristocrat named Tycho Brahe was born who would take Copernicus's work to new heights. Strangely, Tycho (as he is often known) was stolen from his parents as a child by a rich uncle, Jørgen Brahe. The uncle

commanded Tosterup Castle in southern Sweden and later Vordingborg castle in Denmark south of Copenhagen. Young Tycho grew up in comfortable circumstances there. In 1559, he went to the University of Copenhagen to study law. Here he fell in love with astronomy. He was so impressed to see an eclipse in August 1560 unfold exactly as predicted that he began to make his own observations.

When he moved on to the University of Leipzig a couple of years later, he started to keep records. Another astronomical event – a close alignment of Jupiter and Saturn – set him a challenge. According to tables set according to Copernicus's methods, the date was out by days. It was nearly a month out for Ptolemy's projections. Could the young astronomer do better?

He learned how to make exquisite instruments in order to make more accurate measurements of the planets' paths. And he toured the region speaking to other astronomers. One argument with a student in Rostock, Germany, forced him to undertake a sword duel. Tycho ended up with part of his nose lopped off. To hide his disfigurement he had a new artificial nose made of silver and gold.

Tycho continued to travel and develop his instruments. He managed to get funding to build a huge quadrant – a ninety-degree arc with angles and divisions marked on it, against which he could measure the heights of celestial objects above the horizon. It was so big it took many servants to set it up, so he could only make one observation in a night. He constructed a large globe of the heavens, made from wood. And he also dabbled a great deal in alchemy inside his laboratory.

Another astronomical omen set him on a new path in 1572. Wandering out of his lab in the dark one night, to his surprise he saw a new star overhead. He set about making

observations of it, proving that it stayed in the same place relative to other stars and did not shift like a moving comet. We now know that this was a supernova – a star that explodes and brightens at the end of its life, before fading away once again to a husk.

In 1575, the Danish king Fredrick offered Tycho money to set up an observatory on the Danish Island of Hven (now called Ven) in Copenhagen sound. The remnants of the observatory, known as Uraniborg, are evident today. Tycho built it in an Italian style, with a central dome and turrets, surrounded by gardens. He filled it with the best instruments his patron's money could buy. And he used them to great effect, for example to show that a comet lay farther away than Venus, thus proving that comets were celestial and not an atmospheric phenomenon on Earth.

Tycho's instruments were so accurate that they were capable of testing Copernicus' models. If Earth moved around the Sun, then the more distant stars should appear to rock on the sky as our planet rides back and forth through the year – an effect called parallax. But Tycho saw no such shift, and settled on an even more obtuse planetary arrangement than Copernicus – Earth remained in the centre of the Universe, he said, with the Moon revolving around it, while the other planets rolled around the Sun. Today, we know the real reason he saw no shift – the stars are so far away that the parallax is tiny, a hundred times too small for Tycho's tools. (Parallaxes weren't detected until 1838.)

After some fallings out with the king and local staff, Tycho closed Uraniborg and resumed his traveling. In 1599, he moved to Prague to become imperial mathematician to the Holy Roman Emperor, Rudolf II. A new assistant joined him, who would go on to make his own mark – Johannes Kepler.

Tycho died in 1601, as a result of following etiquette during a dinner too strictly. It was considered rude to leave the table before the host, and at one banquet poor Tycho drank his fill but, unable to leave to urinate, his bladder swelled. He was left in excruciating pain and later died suffering fever and delirium.

Kepler became Tycho's successor. He was from far humbler origins. Born in 1571 near Stuttgart, in what is now Germany, his father was a soldier and his mother an innkeeper. Kepler was extremely religious and trained to become a priest. He believed that God had made the Universe to a mathematical plan, as ancient Greeks like Plato and Pythagoras had before him. Man being made in the image of God could, through maths, surely grasp this.

Kepler learned mathematics alongside religion at the University of Tübingen. He was taught astronomy by Michael Mästlin, one of the leading astronomers of the day. Much of the teaching focused on the old Earth-centred models of planetary motions, as suggested by Ptolemy. But Mästlin also showed him Copernicus's account of a Sun-centred Universe and filled him in on the tale of the lost preface to *De Revolutionibus*.

One to look beyond orthodoxy even in his religious leanings, with unconventional views on matter and spirit for example, Kepler saw through Osiander's caution and wondered if such a Sun-centred model might in fact be true. Spotting an open minded and free-thinking scholar, Mästlin persuaded Kepler to teach maths in Graz, Austria rather than become ordained. As he moved away from the life of a priest, Kepler was excommunicated from the Lutheran church in 1612, an act that pained him, but his high position as imperial mathematician kept him secure.

Setting aside the Moon as something other than a planet – he referred to it as a satellite – Kepler started to calculate distances to the six then-known planets according to Copernican theory. There was a lot of space between them, he found, and the spacings were uneven, with far more space between Saturn and Jupiter than between Earth and Mars. Why so? He turned to geometry for an explanation and imagined arranging a series of nested three-dimensional shapes, one inside the other, like Russian dolls.

If Saturn's heavenly sphere was the outer one, imagine a cube sitting within that. The size of sphere that could fit within that cube would be the domain of Jupiter. Put a tetrahedron within that sphere and imagine a ball inside it, and that is where Mars lies. Kepler added other blocks with increasing numbers of sides to represent the distances to Earth, Venus and Mercury, from the Sun.

Representing quite a conceptual departure from the past, Kepler's nested shapes did a pretty good job. But not a good enough one. Tycho's accurate measurements of planetary motions revealed there were still discrepancies. Tycho had left so much data, especially on Mars, that Kepler was able to spot that assumptions of circular motions were the problem. Mars was actually behaving like it moved on an elliptical path, with the Sun just offset from the centre. Kepler was so overwhelmed with data left by Tycho – historical records include almost one thousand sheets of arithmetic – that he described this feat as his 'war with Mars'.

Kepler went on to show that other planets behaved like this too. That planets follow such elliptical orbits is now known as Kepler's First Law. Kepler went on to derive a second law, which says that planets sweep out equal areas in equal times as they move around their orbit. When they

are close to the Sun they move faster, and slower as they move farther away. He published this work in *Astronomia nova* in 1609. Kepler also derived a third law, an equation that predicted how long it would take a planet to orbit the Sun, given its distance from it. All three of these laws hold to this day.

As a religious man, Kepler was so taken with the power of geometry that he took it to be a divine language through which God spoke. He was attracted to the idea that the special ratios of properties of the planets' orbits – such as those expressed through his sequence of nested shapes – were a kind of heavenly chord or charming musical harmony. The concept that music and the physical world were in tune – and the planets represented the 'music of the spheres' – was a fancy of Kepler's predecessors too, including Ptolemy, Pythagoras and al-Tusi, and seen as a way of expressing the beauty and divinity of nature. Kepler, with his mathematical insights, was able to go further and 'identify' the song the Universe was singing.

In 1619, Kepler proposed in his treatise *Harmonices Mundi* (*The Harmony of the World*) that the planets produced harmonic tones as they rounded the Sun. Each sang out a pair of perfect notes, he wrote, like the pure ring that sounds when you run a wet finger around a wine glass. He had to search deep to find perfect ratios, as the orbits themselves weren't in a straightforward sequence. But he found some mathematical relationships in the maximum and minimum speeds of some planets, which seemed justification enough.

Saturn's range of speeds fit a 4:5 ratio, corresponding to a musical interval of a major third, or four semitones, in a classical scale. Jupiter's gave a 5:6 ratio, or minor third, or three semitones. Mars's was 2:3, Venus's 24:25. Earth's

ratio was 15:16. 'The Earth sings Mi, Fa, Mi,' Kepler proffered, revelling in his special insight. Very rarely, such as at the moment of creation, he believed, the planets all sang together in a heavenly chorus. Such aesthetic thinking, very different from the scientific framework we know today, lay behind Kepler's three laws.

Decades later, the fact that planets followed mathematical rules also intrigued British mathematician Isaac Newton, but in a more conventional way. He too had derived three laws, in his case to describe how objects move, as masses propelled by a force. First, bodies remain at rest or move with a steady speed, unless a force changes their motion. Second, applying a force accelerates a body, in the direction of and proportional to the size of the force. Third, to every action there is a reaction. Or as Newton put it, when your finger pushes on a stone, the stone pushes back at you with the same force.

Thinking of that first law, if the planets were not moving in a straight line but in an arc, then some force must act upon them. He imagined the Moon as a sort of cannon ball fired so fast that it sped off into space. A real cannon ball shot from a cannon travelled in an arc, up into the air and then falling back towards the ground. The Earth must tug on it, he reasoned, or else it would fly off in a straight line. If the cannon ball flew fast enough, and the Earth tugged just enough, then it would potentially fly around the Earth, possibly forever. The Moon was held in orbit by such a balance of forces. Newton termed the attractive force of the Earth 'gravity'. He calculated that gravity's force must drop off the farther a body was from the Earth, with the square of distance.

Newton's mathematical hypothesis was clever enough. But what he had done was also profound – showing that the

celestial bodies followed the same rules as objects moving on Earth. Mars and the Moon behaved like a cannon ball, or even an apple falling from a tree. And, he went on, the laws of physics must hold right across the Universe.

‘To the same natural effects we must, as far as possible, assign the same causes,’ Newton wrote in his book *Principia (Mathematical Principles of Natural Philosophy)* in 1687. All massive bodies are endowed with gravity. The Sun has the greatest mass of bodies in the solar system, and the planets are locked in by gravity and revolve around it. The Moon also exerts a gravitational pull upon Earth, which drives the tides, Newton reasoned.

‘Our sea gravitates towards the Moon; and all the planets mutually one towards another; and the comets in like manner towards the Sun,’ he wrote. The workings of the cosmos are a form of intricate clockwork.

As mathematicians pinned down the timings of the motions of the planets, others were trying to take a hard look at them through the then new technology of the telescope. Just as Kepler’s *Astronomia Nova* was published, Italian astronomer Galileo Galilei pointed his spyglass at Mars. He didn’t notice much beyond its bright disk. But he got a surprise when he looked at Venus – it had nightly phases like the Moon, suggesting it must go around the Sun at a closer distance than Earth does.

And Jupiter revealed more – a line of four dots slowly moving back and forth past the planet’s disk. Galileo correctly surmised that these were not stars but moons orbiting Jupiter, implying that the Sun and Earth were not the only bodies in the solar system with satellites. As was common in Europe at the time, Galileo proposed naming them after his patrons, the Medici family, and referred to them himself simply as moons I, II, III and IV. German

astronomer Simon Marius ultimately gave the names we use today to Jupiter's moons, although it took a long time for them to be accepted.

Marius published his observations of Jupiter and its moons in 1614, along with a claim that he discovered them before Galileo. The great Italian astronomer was incensed, and they became fierce rivals. Marius's reputation was sullied for centuries, until 1903, when a group of historians in Holland concluded that Marius may well have made his discoveries independently. Marius's names for the moons stuck, though – Io, Europa, Ganymede and Callisto, who were all lovers of Zeus in Greek mythology. The god Jupiter was the Roman equivalent of Zeus – the king of all the gods and god of the sky and thunder, weather, law, destiny and fate. To this day, we refer to those four moons as the 'Galilean moons'.

Saturn too appeared to have moons, or so Galileo thought. He could just make out two fuzzy blobs either side of the planet, although they seemed to come and go, which puzzled him. In 1659, Dutch astronomer Christiaan Huygens figured it out. The blobs were not moons but a broad disk encircling the planet. The ring must be thin, like a plate, as it seemed to disappear when viewed edge on.

Huygens did also discover a definite moon of Saturn, Titan. A few years later, four more moons were seen by Italian-French astronomer Jean-Dominique Cassini, and named Iapetus, Rhea, Tethys and Dione. To flatter his ruler, together he referred to them as the 'Sider Lodoicea' (Latin for 'Louisian Stars') after King Louis XIV of France. Cassini also discovered that Saturn's ring was split in two, with a gap that is now known as the Cassini Division. Today, astronomers know that Saturn's ring system is made from hundreds of narrow rings made from orbiting blocks of ice.

More than 150 tiny moons have also been detected, many within and close to the rings.

So, the planets were turning out to be far more than wandering stars. And over the next few centuries, as telescopes improved, astronomers would peer at them ever more clearly. Mars, for example, began to show its face. In 1659, Huygens discerned dark blotches, including one that returned to the same position after about twenty-four hours. That implied that Mars spun on its axis at about the same rate as Earth. A decade later, he sketched a white cap on Mars's south pole: the red planet appeared to have polar ice caps much like ours. Jupiter too had a pale spot but in the middle of its face. Cassini reasoned that this might be the snowy peak of a mountain. Venus appeared blue and streaked with pale clouds, much like skies on Earth.

There was much about these distant worlds that was familiar. And that sense of familiarity coloured centuries of thought about the nature and purpose of planets and possibilities for life upon them.

Plurality of worlds

Buoyed by the idea that other planets in our solar system mirrored our own, astronomers' imaginations ran riot. If each star in the night sky was like the Sun, then surely each might also have its own cadre of planets orbiting around it, some reasoned. And, given that Earth hosts life, might not other planets do so as well?

Their minds boggled – not just with the sheer multitudes of planets that might lie out there in the cosmos, but with what that meant. Did it make events and life on Earth more important, or less? What did it say about how the Universe

was created, and for what? Answers were as numerous as the people who posed them.

As early as 1584, Italian philosopher and priest Giordano Bruno argued that the Universe, and thus the number of stars and planets in it, is infinite and all encompassing. Everything is part of the Universe, and its reach may well extend forever. 'We discern only the largest suns, immense bodies. But we do not discern the Earths because, being much smaller, they are invisible to us.' Bruno imagined other watery planets like Earth circling these distant suns.

While his views sound reasonable, and there is much evidence to support them today, they were well outside the mainstream at that time. It had been decades since Copernicus had overturned the dogma that the Earth was at the centre of the Universe, but many members of the Catholic church, as well as other scholars, held on to the idea. Why then were these other Earths circling other stars? To them it made no sense. Referring to Ptolemy's epicycles as 'chimeras', Bruno fell out with the church and moved away from Italy to avoid his powerful critics' wrath. Even so, he ended up being burned at the stake as a heretic in Rome's Campo de' Fiori in 1600.

Half a century later, French thinker René Descartes also came to believe that the Universe was brimming with planets. But he was far more circumspect. In his 1644 book *Principles of Philosophy*, he deployed his craft to artfully dodge the question of whether or not planets existed around other stars. But some of the ideas he came up with are still relevant to studies of planets and how they form.

On the one hand, Descartes denied that there had to be a 'plurality of worlds', as people of the day put it. Other stars must indeed be Suns, he wrote, but they need not host planets. For example, he imagined, some distant suns might

be surrounded instead by vortices of material, swirls of matter caught in eddies like blown leaves on a pavement. On the other hand, he admitted, that didn't mean that distant suns definitely did not host planets as we know them at all – that question he left open. Descartes also proposed that the composition of everything in the heavens and Earth is the same, in a sort of lumpy continuum. Wherever it was, all matter was alike.

To an astronomer of today, Descartes' vision of swirls of matter surrounding distant stars is reminiscent of the disks of gas and debris out of which planets are thought to condense. The planets in our own solar system probably formed as rocks and gas clouds clumped together and swept up more gas around them over billions of years. Descartes was also on the money – as far as we know – in assuming that the make-up of the Universe is much the same nearby and far away. The basic building blocks of atoms hold everywhere. Then again, that broad view wasn't completely original. Some ancient Greek philosophers had argued the same, albeit in a different context and without the firmer scientific knowledge of the seventeenth century. Descartes was hedging his bets.

Philosophical discussions around how common planets were also caught the imagination of writers. For example, French author Bernard Le Bovier de Fontenelle took a literary approach in his 1686 book *Conversations on the Plurality of Worlds*. The book, written in French and later translated into numerous languages over more than a hundred editions, was one of the first popular explanations of the emerging science of astronomy that was aimed at the discerning public.

Fontenelle's book relates passionate discussions between a philosopher and marquise over evenings spent walking in

the moonlit gardens of a chateau, gazing together at the stars. On the first evening the philosopher relays to the lady Copernicus's finding that the Earth revolves around the Sun. Over later night-time strolls the pair revel in the possibilities of life on other planets in the solar system and even beyond, on planets around other stars.

The dialogue flutters as if in a heady romance: 'Said she, I love to see the stars, and am almost inclined to reproach the Sun for hiding them. Ah! cried I, I cannot forgive him for concealing so many worlds from my sight!' The marquise is taken aback. What are these worlds, she exclaims? The philosopher admits his fanciful idea: 'I have taken it in my head that every star may be a world.' This idea gives him pleasure, he says, which is 'a needful accessory to truth'.

A great deal was written at the time about how different planets might be conducive to hosting different types of beings. Astronomers indulged in considering how life forms elsewhere might be accustomed to more extreme heat or cold, or greater or lesser gravity, for example, than Earth. Thinking about such alternatives was one way to explain why Earth is as it is and humans are as they are – on a planet that's not too hot, not too cold, and just the right distance from the Sun.

Borrowing from these debates, for example, Fontenelle's fictional pair agree that, given the differing distances, 'all the inhabitants of Saturn are slow; all those of Mercury are quick'. Earth-dwellers must come somewhere in the middle, but 'we form such a ludicrous assemblage that it might easily be imagined we had been brought together from a variety of worlds'.

Some astronomers, Galileo for one, refused to play those thought games. He thought extraterrestrial life a long shot. In all his observations of the Moon, he declared, he had seen

no water, air or seas, and thus no ingredients for life. In a letter to another astronomer in 1613, Galileo called the idea that there were inhabitants on Jupiter, Venus and Saturn or our Moon 'false and damnable'.

Yet if distant planets were made of the same stuff as Earth, why would they not host life, argued Huygens in his 1698 treatise *Cosmotheoros*? Like Bruno and Fontenelle, he saw no reason why other stars did not host inhabited planets 'as beautiful and as well stock'd with inhabitants' as ours. He, and other philosophers, then tried to tease out the logic of our existence within this vast star-and-planet-peppered Universe.

Why should other worlds be inanimate deserts, full of only rocks and stones, without any animals to relate to a creator God, wondered Huygens, trying to link these arguments to his Christian faith? And if animals exist then surely there must be plants for them to eat and water for them to drink. Other planets, as on Earth, must have air to carry sound and the animals there would have the pleasures of senses, such as taste, smell and touch. Rational beings on these planets must have writing and sciences just like us, he mused. They will be stargazers, live in houses and make music, metals and inventions, he wrote.

With so many possibilities for life on other planets, writers had a lot of material to play with. In a 1752 novella, *Micromégas*, the French author and satirist Voltaire wittily played with scale to take down the way astronomers and mathematicians of his time calculated the extraordinary size or characteristics of extraterrestrials by supposedly applying the rules of physics. He also turned tables on the science of the microscope, which had been invented a century earlier.

The subject of Voltaire's short story is an inhabitant from a planet orbiting the star Sirius. His name is Micromégas, 'an

appellation admirably suited to all great men, and his stature amounted to eight leagues in height, that is, twenty-four thousand geometrical paces of five feet each.' Micromégas rides comets from planet to planet. He reaches Saturn, and befriends a local, who is a 'dwarf' at 'only about a thousand fathoms tall'. He moves on to Jupiter and then to Mars, which is so small he can barely lie down. Then on to Earth, whose inhabitants are so tiny he cannot make them out – apart from a whale and ship, with whom he cannot converse.

Micromégas figures out that there are tiny animals on Earth. He politely addresses the philosophers among these 'intelligent atoms', who hang their heads and decry humans as 'knaves, fools and miserable wretches'. Even the philosophers' duties sound pitiful: 'We anatomise flies,' they remark, 'we measure lines, we make calculations, we agree upon two or three points which we understand, and dispute upon two or three thousand that are beyond our comprehension.'

Micromégas offers them a book setting out the true essence of things, which he leaves at the Academy of Science in Paris. The pages are blank. 'Ay, ay,' the secretary nods, 'this is just what I supposed.'

Voltaire must have enjoyed this salutary poke at the science establishment. I can imagine his pen aimed just as sharply at scientists of today, who spin mind-bending yarns of superhuman intelligence, digital minds, time-travel and more, revelling in their possession of the expert knowledge and thus power of science.

Some philosophers wondered how intelligent extraterrestrials might be. In 1755, German scholar Immanuel Kant supposed that intelligence grew 'more excellent and perfect' with distance from the Sun, in his

work *Universal Natural History and Theory of the Heavens*. Mercurians and Venusians were not as smart as Earthlings, he argued, who were in turn inferior to Jovians (from Jupiter) and Saturnians.

Kant was humbled, though, by the possibility of so many other beings in the Universe. He wrote in his *Critique of Practical Reason* in 1788 that this 'view of a countless multitude of worlds annihilates, as it were, my importance as an animal creature'. Earth is a 'mere speck in the Universe'. It's a common feeling of being small and impotent juxtaposed with the immensity of the Universe.

Planetary purposes

What were all these planets *for* then, and why did they exist? As well as scientists and philosophers arguing about the nature of planets, religious scholars have long been taken by the topic too. After all, if some deity created everything, they must have had a reason. And the existence of extraterrestrial planets might hold moral lessons for us on Earth.

Long before the seventeenth-century debates, philosophers, astronomers and theologians across all cultures have imagined worlds separate from the one we live in. For example, passages in the Qur'an refer to the 'worlds' that Allah created. In ancient India, Vedic scholars writing between 500 to 1500 BCE regarded the Universe as an ocean of space, strewn with planets like islands. They considered that there might be millions of species of living beings, many like humans, many more advanced than us.

According to Hindu theology, extraterrestrial life must be part of the physical world, like us. And it must thus be subject to the principle of reincarnation, or 'samsara', with

death one stage between endless cycles of animation as different forms of life. The endpoints depend on the value of one's 'karma' - a sort of moral bank balance of all the actions one takes in one's lifetime. Those with a positive balance might go on to live in high human castes or even as a god; those lacking may come back as an insect or plant. It's an endless wheel of creation, destruction and rebirth. Potentially, forms of life anywhere in the Universe could be transformed upon death and reappear anywhere else. It's harder to say where in the hierarchy of karma they would be, though.

Similarly, Buddhist texts, such as *Anguttara Nikaya* (*Numerical Discourses of the Buddha*), are sure that the Universe is full of thousands of inhabited worlds and beings of many types and grades. All these worlds and everything on them are subject to cycles of destruction and rebirth.

Meanwhile, Christian and Jewish scholars also struggled to apportion the role of their God in the creation of the planets. And, as improving astronomical knowledge clashed with all these firmly held belief systems, in the eighteenth century debates between science and religion grew especially fierce. The underlying ideas were shared in popular books and lectures and taught and discussed in universities, where they influenced many people.

For example, in the US, John Adams, who later served as the second US president, wrote about whether extraterrestrials might have, like humans, become mortal owing to having committed moral wickedness. Scientist, writer and statesman Benjamin Franklin wrote of how he was so humbled by the vastness of the Universe that he imagined there might be 'many beings or gods, vastly superior to man' watching over their own planets and suns - a departure from the traditional Christian doctrine.

Swedish scientist turned spiritual visionary Emanuel Swedenborg (whose followers are known as Swedenborgians) contended that Christ came only to Earth, but that his message then spread through the rest of the Universe. In a 1758 short work called 'Earths in the Universe' he describes encounters with extraterrestrials – human-like spirits and angels near Earth and other worlds – with whom he discusses their lives, cultures and ways of worship.

Swedenborg saw the planets as serving a bigger purpose: they 'are not empty masses, and created only to be conveyed in their revolutions round the Sun, and to shine with their scanty light for the benefit of one Earth, but their use must needs be more enlarged and distinguished'.

London-based, Italian-born Rabbi David Nieto argued similarly for the existence of life on other planets in his 1714 book *Matteh Dan*, on the basis that they were too glorious to have been created merely to shine light on Earth. Indeed, 'who could suppose that a wise manufacturer would prepare tools worth thousands to make an iron needle?', he wrote.

But many others struggled with explaining the two sides of the cosmic coin. In 1794, British writer and philosopher Thomas Paine fired a shot across the bow of Christianity when he published the first part of his sensational book, *The Age of Reason*. In it he argued that belief in extraterrestrial life and many worlds contradicted the tenets of Christianity – and scattered that system of faith 'like feathers in the air'. In his view, the two beliefs could not be held together in the same mind. And his money was firmly staked on the philosophical logic of life as universal.

Paine rationalised that, as every crevice on Earth is filled with life, so must life be everywhere in the Universe. It did not make sense in his view for a deity to focus just on our

planet, or for other worlds to have their own 'Adams and Eves'. The stories of Christianity were just that, he argued, and not descriptions of the real Universe, or any god that created it. While there are many 'wild and whimsical' systems of faith, many of which may be morally good, there must be only one true religion, Paine wrote, and that is one that is consistent with the world that our senses perceive.

Thomas Chalmers, a rural Scottish parson, tried hard to reconcile science and religion. Some of his drive might have stemmed from having once tried to follow both career directions. In 1815, he began a series of sermons on this topic that drew immense crowds. He turned them into a series of best-selling books, titled *Discourses*, that reached some twenty volumes published in the US as well as in the UK and Europe.

Chalmers' experience at the pulpit and his vivid use of words must have entranced his audience. While astronomy's 'imposing splendour' might well 'dazzle and mislead an inquirer', he admitted, the Christian religion is also open to nature, and indeed to everything in the Universe. After all, he said, the Lord cares for the lilies of the field, and the Psalms describe a heaven filled with divine energy and crowded with splendour. Bringing the two powerful fields of science and religion together made for an even more impressive whole. God is indeed 'nature's architect', Chalmers wrote, and 'there is much in the scenery of a nocturnal sky to lift the soul to pious contemplation.'

He expressed nicely why people are so drawn to the night sky: the Moon and the stars 'are detached from the world, and they lift you above it. You feel withdrawn from the Earth, and rise in lofty abstraction above this little theatre of human passions and anxieties.'

Myriad worlds must exist, Chalmers mused, with days and nights and seasons, and mountains and seas, atmospheres and icy poles like ours – yet so far away that we cannot perceive the detail. He imagined what would happen if Earth was destroyed – through catastrophic volcanic eruptions, floods, collisions with a comet, or the death of the Sun. It is this very fragility and insecurity that leads humans to seek God's protection, he argued, even though they cannot comprehend the breadth of all existence.

Nonetheless, the rational draw of astronomy did lead some people to withdraw from conventional religion. American writer and poet Ralph Waldo Emerson had a deep interest in astronomy and decided to resign from serving as a minister in 1832. In a sermon titled 'Astronomy', he pondered whether the God of the Bible and of nature are one and the same – and concluded not. Earth, as one of many worlds, could not be a mere 'scaffold of divine vengeance', he reasoned. And Copernican astronomy had 'made the theological scheme of Redemption absolutely incredible'.

Scholars suggest that astronomical knowledge might also have been a factor leading British poet Percy Bysshe Shelley to abandon his Christian faith. In a note added to an edition of *Queen Mab*, printed in 1813, Shelley noted how 'the indefinite immensity of the Universe, is an awful subject of contemplation. He who rightfully feels its mystery and grandeur is in no danger of seduction from the falsehoods of religious systems, or of deifying the principle of the Universe.'

In 'On the devil, and devils', which was written shortly before his death, Shelley mused on whether the devil, like God, is also omnipresent across the Universe, like 'salt mixed with water'. Why should the people of Earth be

uniquely susceptible to the devil's temptations, and not the inhabitants, say, of Jupiter? Indeed, there must be a multitude of devils in the Universe, he wrote.

Fellow poet Samuel Taylor Coleridge recalled replying to someone who asked him what God's intention was in creating so many useless great bodies that he did not know, 'except perhaps to make dirt cheap'.

Scientists, theologians, philosophers, the public: everyone had much thinking to do in the face of a growing mountain of astronomical facts. Some remained cautious in their claims, others thought out of the box, and a few had quite a lot of fun with them.

Evolutionary tales

In the decades that followed, parallel advances in geology and biology began to cast shadows of doubt over the more simplistic 'plurality of worlds' ideas. In 1853, British natural philosopher William Whewell published a book called *Of the Plurality of Worlds* in which he marshalled the latest scientific facts to argue against the idea that planets other than Earth were populated. His grounds harked back to religious arguments that the spiritual nature of humans gave us a special place in creation.

Whewell was an all-rounder who, as well as understanding physics and astronomy, was knowledgeable about recent studies of rocks and fossils that showed that Earth was far older than was previously thought (we now know it to be 4.5 billion years old). And, from the relatively recent ages of fossils, clearly Earth held no intelligent life for much of its history (early humans emerged mere millions of years ago). Even on our planet, 'man ... has occupied but an atom of time, as he has occupied but an atom of space,' Whewell

wrote. There was no need to have sophisticated beings elsewhere in the Universe. And anyway, much of it was far less hospitable than Earth.

Life would struggle to survive on a planet orbiting a variable star, which would be scorched regularly by stellar flare-ups, he argued. Gravitational forces would be crushing on any bodies remaining around double stars, where two suns spin around one another. In our own solar system, the Moon is the most likely place for life beyond Earth, he wrote, as it is so close; yet telescopes have shown no evidence for life there, or even any water or air. More distant planets were even more barren, he thought. Take Uranus, Saturn and Jupiter: all are dead.

But Whewell struggled with Mars, which he thought might be akin to Earth long ago, in which case it might even be possible that dinosaurs still lived there. He left room for microscopic forms of life on Venus and Mercury. Perhaps Venusians were protected from the Sun's heat by shells, he mused, like foraminifera, miniscule fossils found in Earth's rocks.

Whewell coined the idea of there being a 'temperate zone' where life might find a foothold in the solar system – what came to be known later as a 'Goldilocks' zone, where temperatures are 'just right', not too hot, not too cold. Earth was the 'domestic hearth' of the solar system, sitting slap bang in the sweet spot for life. Astronomers today still use a similar idea – of a 'habitable zone', where conditions on a planet are tepid enough for liquid water to exist and possibly support life.

Whewell's treatise was roundly attacked. British poet Lord Tennyson poo-pooed the idea that God's only priority was this 'third-rate planet of a third-rate Sun'. Novelist Anthony Trollope had a dig in his 1857 book *Barchester Towers*: 'I feel

sure that there is one man in the Moon at least, if not more,' one protagonist, Eleanor, professes. 'You don't believe in pulpy gelatinous matter?', her suitor Bertie replies, 'why shouldn't there be a race of salamanders in Venus? And even if there be nothing but fish in Jupiter, why shouldn't the fish there be as wide awake as the men and women here?'

In the mid-nineteenth century, the science of life itself was also moving fast. On 1 July 1858, at a meeting of the Linnean Society in London, two similar theories were presented for how different forms of organisms evolved. British naturalists Charles Darwin and Alfred Russel Wallace each set out their observations of how species living in distinct places honed certain traits over generations to suit their environments – a sort of survival of the fittest. These ideas are known as the theory of evolution by natural selection. Both men published papers and writings on them. Darwin wrote them up in his famous 1859 book *On the Origin of Species*.

Evolutionary theory describes how plants and animals constantly shift forms. But it doesn't say how life originated in the first place. In 1871, in a letter to botanist Joseph Dalton Hooker, Darwin wrote pondering if – and it was a 'big if', as he put it – life arose from proteins produced by chemical reactions in 'some warm little pond' on the early Earth, where 'ammonia and phosphoric salts, lights, heat, electricity' and so on were present. With no other organisms to consume it, that protein compound might have made subsequent changes, eventually leading to primitive forms of life, which then evolved away up Darwin's sequence of complexity, or 'tree of life', into the families of species we know today. Scientists have asked similar questions since then, although there is still no clear pathway.

Around the same time, another British populariser of science, Richard Anthony Proctor, took up Whewell's baton and had another look at the possible natures of life on other planets. In his bestselling book *Other Worlds than Ours* (1870), he considered whether Jupiter and Saturn – both giant gaseous planets – should be considered much like suns, or at least as sources of heat for their moons, which could host life.

Even if they don't yet harbour intelligent or advanced organisms, perhaps these grand planetary systems might yet 'be one day the abode of noble races', he wrote. Like Darwin and Wallace's islands, planets are stages upon which life might well evolve, in its own time, in different forms and ecologies appropriate for the place.

'Geology', Proctor wrote, 'teaches us of days when this Earth was peopled with strange creatures such as now are not found upon its surface' – battling monsters, hideous reptiles, huge bat-like creatures and marine behemoths, set amongst wild, humid jungle and crashing oceans, bathed in 'dusky twilight of the primeval day'. Just as today, millions of creatures roamed the Earth, each organism has or had its time.

Proctor writes that 'support of life' must be the primary purpose of this Earth, even if life has only been present for a flicker of an eye in terms of the planet's great age – then considered to be millions of years (now known to be 4.5 billion years). Other orbs too must also be abodes of life.

Thus, the question of life divided into searches for rational intelligent beings, like us, and signs of primitive forms of life, such as microbes. And the question of time loomed large. Looking out into the Universe at all those suns, how many of them might be at a stage similar to Earth, in terms of the evolution of life? Perhaps not many.

Meanwhile, in France, Camille Flammarion was another popular writer about astronomy. In 1862, aged just 20 and whilst still a student at the Paris Observatory, he penned an ambitious book called *The Plurality of Inhabited Worlds*, which was an instant hit. He wrote that science's goal should be to tell us ultimately about where we came from. And without the Universe before us we would only have a sample of one and could never know our place in the cosmos and amongst everything in it.

'The ant in our fields would have infinitely more basis and reason to believe its anthill the only inhabited spot on the globe than we have to regard the heavens as an immense desert in which our world is the only oasis and man is the only and everlasting contemplator,' as he put it.

Flammarion writes powerfully about why we are drawn to gaze up at the starry sky – 'twinkling pearls which tremble in the melancholy azure' – by the 'mysterious idea of the infinite'. Yet a sadness and solitude also descends, he writes, because we can never reach those other worlds. So, we imagine other beings are out there – 'we search for gazes which respond to our own'.

Rather than wondering whether life exists on other planets, Flammarion suggests that a better question to ask is why it has appeared here at all. Humans should marvel that we are so well suited to our planet, with lungs to inhale oxygen fuel from the air and minds capable of doing science to learn how our world works. All animals on Earth, from birds and insects flying in the air in bright sunlight, to fish and crustaceans living in the blackness of the deep sea, evolved hand in hand with the state of our planet over millions of years. Why shouldn't life flourish elsewhere, in different conditions not much more extreme?

Yes, but how likely it is? Alfred Russel Wallace took Flammarion's view several steps further in his sweeping 1903 book *Man's Place in the Universe*. After reviewing the state of astronomy and the arguments for the plurality of worlds, the evolutionary biologist concluded that on the balance of probabilities humans' place in the Universe 'is special and probably unique'. His reasons included the special place in which Earth sits – at a modest distance from the Sun, within a cluster of other stars, all slap bang in the plane of the galaxy. Surely it was no coincidence that humans arose here.

In an appendix added the following year, Wallace accused believers in multiple extraterrestrial worlds of not having weighed the evidence of how improbable the conditions were to foster higher forms of organic life from the elements that exist upon the Earth or in the Universe. Each special factor made the chance of life more and more improbable. Wallace put the probability at a whopping one to one million to the power of eight (that's one million times one million, eight times). Admittedly, that was a vague estimate: but anyway it was, in Wallace's view, really really really unlikely.

To put this another way, Wallace drew on evolutionary theory, arguing that biologists knew of no species on Earth that had ever arisen independently in two different places or times, having evolved from different ancestors. Evolutionary forces tend to diverge, not converge. The fact that no two places are the same, either chemically or geologically, means that any organism growing in one place will not be found in exactly the same form in another. Nor can evolutionary paths be identical even over time. Through an evolutionary lens, the probability of human existence was even more paltry. Each twist and turn on our planet over billions of years has led to us, and the other organisms that

also call Earth home. There's no way to repeat that sequence – anywhere, ever.

Wallace acknowledges that a similar being with a mind and spirituality might have arisen elsewhere in a different form. Even so, he argues, the very things that set humans apart from other animals put us high up the evolutionary tree. Even if our physical characteristics might have been paralleled on another world, our intellectual and moral natures cannot have been. Thus, a human-like presence on another planet is essentially impossible. We belong here.

Mars madness

This argument that, chances are, life is incredibly rare in the Universe, held sway for many decades. And telescope observations increasingly deadened ideas amongst scientists that the other planets in our solar system were inhabited by fantastic beings. But Mars continued to niggle.

By the late nineteenth century, much had been learned about Mars through using telescopes – it rotates, has icy poles, some sort of murky atmosphere, mountains and perhaps seas. William Herschel's belief in the 1780s that 'the analogy between Mars and the Earth is, perhaps, by far the greatest in the whole solar system' stuck. Maps of Mars became increasingly intricate. Italian astronomer Giovanni Schiaparelli named the features, as they are known today, after classical landscapes, such as Syrtis Major, Elysium, Mare Sirenum and Olympus Mons.

On 5 September 1877, Mars came closer in its orbit to Earth than it had in a generation. As both planets circle the Sun, sometimes they both sit near one another on the same side of the Sun. And because they follow elliptical not circular orbits, every eighty years or so they are

exceptionally close, with Mars appearing particularly bright and fiery opposite the Sun in the night sky – at so-called ‘opposition’.

When this happened in 1877, astronomers rushed to observatories and mountaintops around the world, from Rio de Janeiro to Madeira and Mauritius. Some hoped to triangulate the planet’s distance by noting slight differences in its position relative to adjacent but more distant stars as measured from places far apart (a phenomenon known as parallax). Others hoped to snatch a better glimpse of the planet’s rocky surface – and potentially, they hoped, red-leaved forests and vegetation revealed by receding ice at its late-summer poles.

At the US Naval Observatory in Washington DC, Asaph Hall also turned his telescope towards the red planet. It wasn’t the best site for making astronomical observations, drowned out by light from the city. But he did make a discovery over several nights in mid-August – he distinguished the two satellites of Mars, Phobos and Deimos. They were named after the horses – Phobos (fear) and Deimos (panic) – that pulled the chariot of the Greek war god Ares, who is the counterpart to the Roman war god Mars.

On 31 August the *New York Times* published a tongue-in-cheek column musing on the implications of this discovery. It teased astronomers for cautiously assuring the public that Mars was uninhabited on the basis that it had no moons; tides were thought by some to be important for life to originate. Now two Martian moons have been found, surely that case no longer holds, the columnist explained.

Admittedly this argument was weak, it went on, but no intellectuals have rebutted it. Again, writers poked a finger at the scientific elite. ‘No wise man argues with a scientific person,’ the journalist declared emphatically. ‘The latter can

always overwhelm him with unsavory scientific terms, to the use of which no self-respecting man can descend.'

The whimsical column went on to imagine that, if the same laws of physics hold on every planet, then just as myriad cats serenade the Moon from back fences on the five continents of Earth, Mars too must be full of felines praising its moons from many back fences. And with two moons, Mars must have twice as many cats, in proportion to its size relative to that of Earth. 'When both of these moons are at the full, and the feline millions of Mars are joining in glad chorus, the effect must be in the highest degree sublime, not to say nice,' the gleeful columnist wrote.

That *New York Times* article opened by pointing out how peculiarly Mars is laid out - 'the continents being pierced with long and narrow fjords, as if the planet had been expressly designed for the Summer cruises of the New-York Yacht Club'. These dark streaks on the Martian surface had been long noted by astronomers - Italian Jesuit astronomer Angelo Secchi described them in the 1850s as 'canali', meaning channels or grooves. But this meme really took off after 1877 when Schiaparelli, then the director at Milan's Brera Observatory, published yet more detailed sketches of the red planet's features, made more evident when Mars came especially close.

Schiaparelli's drawings show a mesh of criss-crossing dark lines across the disk of the planet, like scars on Mars's ruddy face. He thought the streaks, which he also termed 'canali' in the Italian language sense, might be canyons or rivers, but the English mistranslation to 'canals' stuck awkwardly. And, for a century, the canals took on a life of their own in studies of and writings about Mars.

Schiaparelli was shortsighted and red-green colour blind, and the linear features might well have stuck out as his

eyes were sensitive to contrasts. Originally trained as an architect, Schiaparelli was adept at transcribing what he saw. Yet his accounts of his observations of the canali also suggest that they were somewhat tenuous apparitions, on the 'limit between visibility and invisibility'.

He also struggled to tell the streaks' true colours, whether they were dark red or grey, and referred to his vision as 'almost that of a chiaroscuro made with Chinese ink upon a general bright background'. In subsequent years, Schiaparelli started to see the canali doubling up as his vision began to fail him. Around 1900, when he saw the canali were also appearing deformed, he decided to bid farewell to the markings on Mars.

With astronomers' fallible eyes still at the receiving end of the telescope, descriptions of what Mars looked like were very much in the eyes of the beholder. John Herschel and many others wrote of the ruddy red hues of bright regions and of blue-green tinges apparent in darker patches. Angelo Secchi, who used pastels to paint Mars's face, needed a slew of colours, from reds and yellows to blues and greens. Percival Lowell, one of the most prominent perpetuators of ideas about Martian canals, saw washes of 'robin's egg blue' and 'roseate ochre'.

In one spot, Lowell reported witnessing a colour change from blue-green to brown, suggestive to him of vegetation that had been ploughed up, as in a farmer's field. Some astronomers since have suspected that some of these vivid colours might have been artefacts of the particular type of telescope Lowell used – a 'refractor' using large lenses that are prone to colour aberrations. Later observations with 'reflecting' telescopes, which use mirrors instead to focus light, tended to show a more monochrome planet, with shades of salmon pink or warm grey. Another complication is

that the eye often perceives strong colours alongside complementary ones, to accentuate differences. Two red shades sitting next to one another might appear to have green tints in one as a way to distinguish them.

Such illusions might have supported widespread beliefs at the time that the Martian surface was a living world, with seasonal and even intentional changes in its vegetation. Tales proliferated about a drying and dying landscape, carved by vast irrigation works that were built to feed a vanishing civilisation. Vast canals were in the news then on Earth – the 193-km-long Suez Canal opened in 1869 in Egypt, connecting the Mediterranean Sea to the Red Sea through the Isthmus of Suez, and offering a faster route for vessels to travel between the Atlantic and Indian Oceans.

Still, most professional astronomers scoffed at such suggestions. They noted that structures the size of the canals drawn by Schiaparelli were unlikely if not impossible, stretching as they did across whole hemispheres of the planet, far surpassing any engineering feats on Earth. But some astronomers were more circumspect, and their observations fed what can only be called Mars madness.

Although Lowell had no formal training in astronomy, the Harvard-educated Boston businessman was an enthusiast, and avidly read books like those by Flammarion. In 1894, he moved to Flagstaff, Arizona, to make observations of Mars from a private observatory he had built on a hill outside the town, far from the pollution of city lights. The observatory, named Lowell Observatory, is still in use.

Lowell worked there with astronomer William Pickering (brother of Edward Pickering, the director of Harvard College Observatory), who was a firm believer in Martian canals. After observing Mars in 1892 from Harvard's Arequipa Station in the Andes, Pickering's results – the apparent

identification of forty new lakes on Mars as well as snowfalls and melts – were sensationalised in the *New York Herald* newspaper, and duly disputed by other astronomers.

Lowell, like Pickering, strongly believed the canals were real and mapped hundreds of them as he surveyed the red planet. He published his first set of observations and speculations in 1895 in his book *Mars*. Two more were to follow: *Mars and its Canals* (1906) and *Mars as the Abode of Life* (1908). They proved to be highly influential.

In *Mars*, Lowell set out the case for the possibility of highly civilised forms of life on the red planet, although he left the nature of any current or past beings open to question. First, he ascertained that Mars has an atmosphere, albeit thin – ‘thinner at least by half than the air upon the summit of the Himalayas’ – and with a similar composition to that on Earth. The Martian climate, he wrote, is mild and the air contains enough water vapour to produce clouds and seasonal frosting and thawing of the polar caps. Lowell described observing a blue band of bays emerge around the pole as the ice cap melted, ‘like some Martian grotto of Capri’, only to disappear again.

Tracking seasonal changes in colour across the planets’ face, Lowell concluded that the blue-green patches must be vegetation. But the majority of the planet was barren desert, with fresh water in scarce supply. Lowell mused that because Mars is smaller than Earth, it would have cooled more quickly, and thus must be more evolved geologically. Oceans might have dried up, leaving water to retreat into cracks and caverns. The polar melt was the only remaining source of surface waters. Thus, Lowell imagined, ‘if there be inhabitants, then irrigation must be the chief material concern of their lives.’ The canals, then, must have been built to drain water from the polar sea.

Schiaparelli's canals must have been designed by a draughtsman, Lowell figured. They were incredibly long and straight, stretching for more than one thousand miles along great circles, yet also exceedingly thin, only thirty or fifty kilometres wide. Also, the lines were not randomly placed on the Martian globe; several intersected at a single point, which he assumed might be an oasis. Such crisp details would only be visible through a telescope if the air was perfectly still and clear, he reasoned. That was why others have missed seeing them: 'To look for the canals with a large instrument in poor air is like trying to read a page of fine print kept dancing before one's eyes.'

Thus, Lowell concluded, whether inhabited now or not, Mars is an old world, with a craggy face. 'His continents are all smoothed down; his oceans have all dried up.' The red planet's fierce name is a misnomer, Lowell wrote, which must have confounded the ancients reading its omens: 'although called after the turbulent of the gods, he is, and probably always has been, one of the most peaceful of the heavenly bodies.' And so too for the others. 'With Mars so peaceful, Jupiter so young, and Venus bashfully dropped in cloud, the planets' names accord but ill with their temperaments.'

Lowell's claims about Mars were sidelined by mainstream astronomers, and he and other popularisers came in for a lot of flak. Edward Holden, director at California's Lick Observatory wrote in a newspaper article in 1895 of how 'reckless theorising' about life on other worlds was having a harmful effect on readers. Journalists wanted to report certainties, he wrote, and sometimes astronomers did not have them. Yet scientists were duty-bound to be 'scrupulously exact' in their dealings with the public, who have 'a right to know where certainty ends and speculation

begins'. Alfred Russel Wallace also wrote a book refuting Lowell's arguments, describing the idea of the Martian waterways as 'the work of a body of madmen rather than of intelligent beings'.

But Lowell was a colourful writer and speaker and his vivid descriptions stuck in the public mind. 'Mars fever' broke out, amongst scientists and the public alike. Amongst many striking reports, which are hard to believe today, physicist Nikola Tesla, while working on early radio receivers in Colorado, declared that he had detected repeating signals coming from Mars. In 1901, he told an interviewer that he was becoming increasingly convinced that he was 'the first to hear the greeting of one planet to another'. News followed from Lowell's observatory in Arizona of a shaft of light being seen emanating from Mars. It was proposed to build a set of mirrors in Texas to send a signal back.

The press loved it. Will the riddle of the canals of Mars ever be solved, they mused? Well, yes. With no answers in sight, and World War I on the horizon, off-planet interest amongst the public waned. Better photography and observations eventually ruled out the canals convincingly. Lowell, staunch to the end about what he had seen, shrugged it off. He remained a household name but also a contentious one, ostracised by many of his colleagues.

Lowell also made disputed observations of other planets, including claims of having seen a 'spot' on Venus's otherwise flawless face. Some historians have since argued that this might have also been an optical illusion brought about by reducing the aperture of the telescope so much to observe the planet in the bright twilight sky that it projected an image of the back of the astronomer's eye.

Yet some of Lowell's ideas provoked real discoveries, including that of Pluto. Believing that the motions of Uranus

and Neptune were being distorted by the gravitational pull of another planet, which he dubbed Planet X, Lowell started a campaign to discover it in photographs. A similar technique, to explain slight deviations in the motion of Uranus, had led to the discovery of Neptune in 1846. Lowell didn't manage it, but Pluto was eventually discovered near the expected location of Planet X in 1930 by Clyde Tombaugh, working at the very same Lowell Observatory. What seemed like vindication was actually chance, however, as we now know that Pluto is too small for its gravity to affect the larger planets' motions much, and the mass of Neptune was then uncertain.

Lowell's legacy has lived on, too, in the siting of observatories on remote clear sites away from towns, as well as in astronomical techniques. Lines from *Mars and its Canals* engraved on Lowell's mausoleum at his observatory reveal his dedication and conviction: 'Astronomy now demands bodily abstraction of its devotee ... to see into the beyond requires purity ... and the securing of it makes him perforce a hermit from his kind ... he must abandon cities and forego plains ... only in places raised above and aloof from men can he profitably pursue his search.'

They also acknowledge the challenges of breaking new ground in science, noting that any astronomer must 'wait for mankind's acceptance of his results ... for in common with most explorers he will encounter on his return that final penalty ... the certainty at first of being disbelieved'.

Lowell and Schiaparelli's visions also lived on in other ways – through socio-political thought and science fiction. To them, the fact that Martians could make such splendid canals indicated that these planetary neighbours must be more civilised, or at least have a smoother running and more accomplished society, than humans on Earth. Building

of the Suez and Panama canals had been fraught with political squabbles, labour unrest and deaths, as well as engineering difficulties and delays. Martian engineers evidently fared far better. What lessons might be learned?

Here the two astronomers differed – along lines that Europeans and Americans might find familiar today. Schiaparelli saw those achievements as a sign that Martians operated under a system of collective socialism, which had allowed them to perfect their mathematical, scientific and engineering know-how. Mars was surely a place where intellectuals were respected and knowledge was turned to managing the rougher edges of nature, he mused.

Lowell imagined a different society, a paternalistic hierarchy delivering political unity as a result of evolutionary laws – a harder-edged ‘survival of the fittest’. Lowell believed that natural selection would result in a meritocracy, with the most able at the top, and everyone in their proper place below. Martians, a more established and aristocratic race driven by the necessity to live on a drying planet, must have achieved the ordering of resources, labour and political will needed to survive there, he thought. Earthlings plainly have not. Especially in his later years, Lowell railed against any impediments to ‘evolutionary progress’ in US society, from immigration to multilingualism, unions and pensions to women’s votes.

While their politics diverged, both men believed that Martians had an ideal society – the planet’s surface was a stage set for utopian dreams. Yet the inhabitants also had to deal with a host of environmental difficulties, such as dwindling water supplies. The more scientists learned, the harder it got for life forms on Mars as more challenges to survival stood in their way. But writers continued to wrestle with these political and existential problems – and what they

implied for humanity – through more than a century of writing about fictional visits to the red planet and others.

Projected dreams

In the late nineteenth and early twentieth century, novelists cast away their intrepid and inventive heroes on Martian expeditions, as imperialist explorers were doing to the poles and other remote parts of Earth. Fictional communities on Mars had plenty of scope for exploring alternative socio-political norms, from Communism to war and equality between the sexes.

It was a time of great change. Science and technology were developing fast and the industrial revolution was accelerating, sending shockwaves of change through societies around the world. No wonder writers were keen to explore what these modernising societies might look like on the blank canvas of Mars. And they took a lot of the portrayals of landscapes and putative Martian societies straight from Lowell and Schiaparelli's writings.

Mars is regularly depicted as an arid planet, worked by an intelligent advanced civilisation. For example, in Percy Greg's *Across the Zodiac* (1880), the hero lands on a world with a pale green sky and pink clouds. Around him he spies signs of civilisation – rectangular fields and domesticated animals (resembling antelopes and unicorns), a raised road and the metallic glint of a distant city.

The book narrates the records found in a crashed spaceship that had travelled to Mars and back half a century before. Greg's ship is named the 'Astronaut' – in what was perhaps the first time this term appeared. It might have been taken from the 'argonauts' in ancient Greek tales, the

sailors on the ship *Argo* who accompanied Jason in his quest to find the Golden Fleece.

On Greg's Mars, the locals prove to be a lot like humans. They inhabit a conservative society, where women's freedoms are curbed. Female Martians are clad modestly in loose robes and veils and rarely leave their compounds. The Martian host tells his visitor of how the society came to be that way, through cycles of political squabbles driven by envy and inequity. Land once owned by elites was taken away and property and money banned; everyone was allotted a portion of basic food and clothing, in a form of communism. The production of unnecessary or vanity products was stopped, to eradicate envy, but idleness became the norm and famine followed.

Martians retreated to small communities, run on 'principles of private ownership and the permanence of household ties'. They embraced science and made advanced weapons that enabled them to fend off revolts, and to finally bring about peace. Yet all is not well on Greg's red planet. There's no place for religion, which Greg's hero tries hard to resurrect, and cold logic has withered family ties, such that children are raised by the state.

Greg's lesson isn't crystal clear, but he does expose the inhumane aspects of both elite leadership and communism, and the tendency for women and children to fare worst in harsh political systems. On his Mars, parental love is scorned as a base instinct; mothers must leave an 'indelible mark' on their child to be able to recognise them in society later. Through centuries of social evolution, the planet has ended up as an emotionless place, with a standoff between the sexes, and presumably a dwindling population.

Two American women writers, Alice Ilgenfritz Jones and Ella Merchant, paint quite a different picture of strong

Martian women in *Unveiling a Parallel* (1893). The protagonist meets an elegant Martian woman called Elodia: 'She was not like any other woman - any woman I had ever seen before. You could not accuse her of hauteur, yet she bore herself like a royal personage, though with no suggestion of affecting that sort of an air. You had to take her as seriously as you would the Czar.'

The Earth-traveller notices her brother's egalitarian attitude toward her: 'There was none of that condescension in his manner that there often is in our manner toward the women of our households.' Jones and Merchant's Martian women, it seems, had wealth, suffrage, opinions, respect, property and offices of state: they also got drunk, smoked and bore children out of wedlock, all with the blessing of the Martian state and religion. It truly was another world.

The red planet and others have also been widely used as stages for contemplating different types of utopias. In *Aleriel* (1883), Anglican priest Wladislaw Somerville Lach-Szyrma contrasts two ideal societies - a social one on Venus and a technological one on Mars - with the hard inadequacies of our own planet. It is a sobering admission of humanity's struggles and the human condition. Perhaps he hoped that we might one day learn our lessons and live happily and peacefully, like the putative inhabitants of our neighbouring planets. Or perhaps he thought that humans can never be at peace, even if we travel to new worlds. We are destined to bring our baggage with us.

Aleriel, the novel's namesake, is a winged being, originally from Venus, who travels the solar system. Venusians are soft, gentle and simple and know nothing of the debauchery of Earthlings. Landing on Mars, Aleriel depicts Martians as intelligent, with a language, alphabet, and steeped in scientific knowledge. Much like Greg's account, Lach-

Szyrma's Martians describe how their planet was one riddled by war but is now peaceful and prosperous. Selfishness was banned and only the virtuous and wise were promoted to positions of power. Nevertheless, there is a harsh penalty for not playing by the rules – death. Aleriel asks us to consider both types of ideal societies, their strengths and weaknesses.

Settling on Earth, though, Aleriel finds it 'a sad, a sorrowful world', full of sin, death and suffering, disease and war. He tells of how he has 'beheld man in his various races, in his struggles for higher things, in his sorrows, his agonies, his death'. He has seen 'the wretched selfishness of men grasping for self only; the weak crushed by the strong, and the strong still insatiate'. Earthlings have a long way to go. This idea of a visiting 'angel' to warn us about our sins has been widely used in science fiction since, including Robert Heinlein's *Stranger in a Strange Land* (1961) and Walter Tevis's *The Man who Fell to Earth* (1963).

Yet the nature on Earth is beautiful, Aleriel says, lit with silver light from its satellite and with gem-like islands and flakes of snow. With its great oceans and continents 'it is in some way fitted for happiness'. Yet 'man has no hope of perfect happiness', at least in this life, he notes. This description certainly hits home today, as we humans seem firmly set on destroying that beauty, through climate change and other forms of environmental over-exploitation. It's also a reminder that these concerns are not just twenty-first century ones, our present – even our scientific framing – is wrung through with echoes of the past.

The novel's lens is firmly focused on our neighbouring rocky worlds, as places we can relate to. When Aleriel visits the outer planets and their moons, he finds they are mostly elemental places, with copious clouds, deep oceans and

blazing fire. Jupiter and Saturn hold no lessons for humanity, Lach-Szyrma explains in the preface: 'they are little more than bold deductions from observations or probabilities suggested by them.' By contrast, Venus and Mars had lengthy cultural imprints he could draw upon, which most readers would recognise.

Soviet authors meanwhile used science fiction as a means to explore the socio-political constructs of communism, and also environmental distress, as their nation wrangled with both. Even before the revolution, in Bolshevik activist Alexander Bogdanov's *Red Star* (1908), a revolutionary mathematician named Leonid meets a Martian who takes him to Mars. Leonid is impressed by the planet's red 'socialist' vegetation and its gentle, old, denuded landscape. He sees the equality of Martian society, again long won on this ancient world.

But Leonid slowly realises that all is not so rosy on the red planet. Mars is ahead of Earth in its social revolution, but also in its ecological over-exploitation. With little rain, Mars is struggling to maintain its water supplies. Forests have been chopped down after coal ran out. Food is scarce. Overpopulation is becoming a burden on Mars's limited resources, and other nearby planets – Venus and Earth – are being eyed for possible colonisation. After a mining trip to Venus comes up short, Earth is singled out as the next place to plunder for resources. Leonid panics and murders one of the crew. He returns home, only to be told it was all a dream, and is left to wonder at the gap between socialist utopia and real life.

As similarly egalitarian yet flawed Mars greets protagonists Los and Gusev in Aleksey Tolstoy's story *Aelita* (1923). Los is a bit of a dreamer, having come to Mars to seek adventure, only to fall in love with Aelita, the daughter

of the Martian ruler. Gusev is a harder sort. He's a dedicated communist who wants to bring back a letter from the Martians expressing their willingness to join the Soviet Union.

Gusev sees two sides of Martian society. Affluent, finely attired people promenade in lush garden squares as golden flying boats float over the city. Meanwhile, wizened workers in shabby factories eke out their 'dismal, hopeless, ant-like existence'. 'Thousands of years of boredom' waft from the city's indistinguishable brick streets, home to an underclass of drugged-out Martians. In a typical plot, unrest erupts between the elites and workers, and Gusev and Los escape and return to Earth. It was far safer to publish critiques like these set on another world.

Tolstoy's story, rich in detail and action, was turned into a screenplay in 1924, with futuristic sets that inspired the *Flash Gordon* space opera in 1934 and its many sequels. A century on, in films like *The Martian*, the red soils of Mars are still being used as a stage for exploring humanity's discomfort and the uncomfortable chafing of idealism and reality.

The themes tackled by many science-fiction writers darkened further after the Second World War as the world tried to juggle the promise of new technologies with the exhaustion and disillusionment of human society after what it had gone through. Science offered better health and more food, but it had also unleashed the fundamental forces of physics, as exposed so brutally with the dropping of two atomic bombs on the Japanese cities of Hiroshima and Nagasaki by the Americans in 1945. Numerous writers wanted to work through these conflicting feelings and swelling concerns about population, resources, reconstruction of cities and protection of the environment.

Ray Bradbury's *The Martian Chronicles*, published in 1950, satirically lays bare America's obsessions of the era, from gun-toting and drinking, to materialism, capitalism and the shadow of atomic war. The book made no claim to be science fiction. As Bradbury explains in his preface, the tale, told in shimmering vignettes and allegories, has the essence of myth. 'Science and machines can kill each other off or be replaced. Myth, seen in mirrors, incapable of being touched, stays on.' And myth can be powerful. Indeed, 'even the most deeply rooted physicists at Cal-Tech accept breathing the fraudulent oxygen atmosphere I have loosed on Mars,' he wrote.

Bradbury's Martian inhabitants, who themselves left Earth a century before to escape war, are ephemeral beings, crafty at conning incoming Earthling crews into believing that the dead cities on Mars are akin to small-town America. The human crews initially are scouts – expeditions to find out how habitable it is on Mars, leading the way for further shipments of people eager to avoid the looming threat of nuclear war on Earth. And it is not long before they do come.

The 'men of Earth' came for all sorts of reasons, Bradbury writes, because they were afraid or unafraid, happy or unhappy, felt like pilgrims, or did not. They left 'bad wives or bad jobs or bad towns; they were coming to find something or leave something or get something, to dig up something or bury something or leave something alone.'

Read today, there's a lot here that still resonates about the push to resettle fresh land, wherever it is, even off Earth. The United States has this deeply embedded in its origins, as European settlers moved west into newly acquired territories, with little thought to the prior inhabitants. And it is reminiscent too of descriptions of

future bases on the Moon and one day Mars, established for mining minerals, or just to go there for the sheer hell of it. I wonder whether and how these stories will play out in future reality.

On Bradbury's Mars, the first towns were mining towns. The men set to work with their hammers, knocking up shingle-roofed cottages, trying to 'bludgeon away the strangeness'. And when the carpenters had finished, 'the women came in with flowerpots and chintz and pans'. Then the church came. Then the musicians. Politicians and robots. And the old. Finally, hot dogs.

Twenty years further on and the Mars of Bradbury's chronicles was 'a tomb planet'. The war-torn shell of Earth burned in the sky, fiery green. The new Martians could not go home. This was their planet now. It's a harsh warning to us all, as we trash our beautiful home and fight one another for land, while those with power and money eye a fresh beginning in a different world.

Alien invasion

Bradbury's original Martians melt away like ghosts, outnumbered by the latest influx of inhabitants from Earth. But other authors have imagined far more confrontational interactions.

For example, in 1897's *Two Planets*, German author Kurd Lasswitz wrote of polar explorers who are surprised to find Martians camped at the North Pole. The extraterrestrials take some of the explorers back to Mars to show them their advanced society. Again, Mars is dry and its inhabitants have had to build canals to sustain themselves. But it turns out that the Martians also have an invasion of Earth on their mind, to gather solar power.

The Americans and British unleash their militaries, but to little avail. The Brits are roundly routed and the Martians set up authoritarian rule there. The US holds out, just, for a while. Eventually the people of the world manage to rebel, by setting up an underground movement and stealing technologies. An uneasy peace is called. But the world is forever changed.

At around the same time, British writer H.G. Wells had similar thoughts about what Martian invasions might tell us about ourselves. It was not long after another opposition of Mars, in 1892, when the planet came unusually close to Earth. The newspapers, as always, were full of the din of speculation. And even sober scientists were keen to join in.

English scientist Francis Galton (who studied genetics and intelligence amongst other things, and has been criticised for his extreme views on eugenics) wrote a colourful letter to the British newspaper *The Times*. In it, he postulated that it would be possible to use a line of mirrors to flash light signals at the nearby planet 'that the inhabitants of Mars, if they have yes, wits, and fairly good telescopes, would speculate on and wish to answer'.

Flashing 'one, two, three' might garner a similar response, he suggested. The only difficulty would be doing so at night, when the Sun could not be used as a light source. Other ideas for communicating with Martians included using telegraph technology, which the writer Flammarion suggested might be feasible if Earth's magnetic field could be harnessed to bounce sounds through space.

In August 1894, a ripple of excitement was created when an observatory at Nice in France reported seeing a light coming from Mars. The science journal *Nature* noted it in an editorial, suggesting cautiously that in all likelihood it might have come from forest fires or glints on snow rather than

anything too improbable – ‘although it is to be expected that the old idea that the Martians are signalling to us will be revived’.

Wells turned that idea on its head in the opening of his serialised book *The War of the Worlds* (1898), in which the Martians turn their telescopes on Earth. The puny organisms on our planet appear like microbes under a microscope, complacent and unaware that they are being watched ‘keenly and closely’ by intelligences greater than theirs. ‘No-one gave a thought to the older worlds of space as sources of human danger,’ Wells wrote. And soon came ‘the great disillusionment’. His account changed the depiction of extraterrestrials from humanoid angels to something unimaginable.

Wells refers to the Nice Observatory flash, concluding that the blaze must have been ‘the casting of the huge gun, in the vast pit sunk into their planet, from which their shots were fired at us’. Soon after, a vast incandescent gas cloud squirts from Mars to Earth. The protagonist hears of it from an astronomer, with whom he spends a night in an observatory viewing Mars, silent but for the ticking clockwork of the telescope. Mars is ‘a little thing’, ‘silvery warm’, spied through the slit in the roof – ‘an oblong profundity with the stardust streaked across it’.

The pair witness another missile of gas rushing out of the red planet. The astronomer scoffs at those who think these flashes are signals from inhabitants. ‘The chances against anything manlike on Mars are a million to one,’ he insists. Yet more people on Earth witness these eruptions over the coming nights. And then come the shooting stars.

The Martians invade en masse, rampaging across southeastern England and taking London. People fight back but ultimately the beasts face their own fate, dying off

suddenly from some unknown disease. Life returns to something like normal, but it is not. In the back of all minds now is the Martians' probable return.

In Wells's crosshairs is the arrogance of the human race, the supposition that we are the pinnacle of creation, of evolution. He is also critiquing colonial powers, especially the British empire – the Martians are only doing to us what we do to others, be they other races or animals like the dodo.

Wells was well versed in the science and lore of Mars. He wrote several essays and short stories featuring the planet, as well as a textbook (with Richard Gregory) about Martians and canals. He also attended lectures on biology and evolution in London by Thomas Henry Huxley, a follower of Charles Darwin's ideas about natural selection. Although Wells knew that conditions on Mars were not vastly different from those on Earth, he imagined that evolution took a different path on that planet. Humans need not have been the end point. The idea that there were humans on Mars was anthropomorphism, he argued, projecting and seeing only our own experiences without acknowledging those of others.

For the next fifty years, many more science-fiction writers raked the Martian coals. Many stories were like medieval romps where brave heroes fought off aliens to rescue princesses, in the style of the Arabian Nights or King Arthur myths. From Gustavus W. Pope's *Journey to Mars* (1894) to Edgar Rice Burroughs' *A Princess of Mars* (1912) and Marcianus Rossi's 1920 *A Trip to Mars*, their protagonists go on luxurious and outlandish vacations – an out-of-this-world 'grand tour', replete with jewelled architecture, silk and fur costumes, fabulous creatures, lush scenery and more.

Others were boyish adventures, unsullied by romance or the female sex. Burroughs' novels use Mars' character as the god of war, creating a planet full of conflict. Alpha males feature prominently, tied to eugenic ideas about the survival of fittest. Racism is rife. Pope too mentions the yellow-, red- and blue-skinned races on Mars, but rules out mixing. Boys' books of science fiction also came out about this time, including Fenton Ash's *A Trip to Mars* (1909, not to be confused with Rossi's book of the same name) and Roy Rockwood's *Through Space to Mars* (1910). And mass produced sci-fi books spread.

Yet Wells's vision of slimy extraterrestrial 'otherness' lingered long and vividly. In 1938, American actor and filmmaker Orson Welles broadcast a radio series based on Wells's *The War of the Worlds* that transposed the events to US towns. The American public reacted in panic, imagining that it was actually happening. They were jittery, after all it was Oct 30, just before Halloween, and the storm clouds of the Second World War were gathering.

A *New York Times* article on 24 July 1939 (weeks before the German invasion of Poland) wrote of the latest 1939 opposition of Mars as something that would once have been taken as a bad omen: 'For Mars, planetary symbol of the war god, is blazing with baleful splendour in our southeastern sky.' But we should not worry, it went on.

For there were no men on Mars. And 'as for the weird creatures of Wells's imagination, New Jersey can feel absolutely safe.' Yet, just think - 'a single living plant on that barren surface would be a link connecting us with the remotest reaches of the heavens.' We exist; our conscious minds exist; and who knows what might happen when humanity is gone, the writer mused. 'Germ cells on other

worlds will begin again the majestic march to consciousness and reason. At least, we may hope so.'

Nonetheless, astronomers and some militaries wanted to keep an eye on things out there just to be sure. In the 1960s, American radio astronomer Frank Drake began to regularly point his dish at two stars and scan them in a frequency band characteristic of hydrogen. The idea was that any intelligent beings on planets around those stars might send messages in such a universal key. Soviet astronomers also listened. So began the Search for Extraterrestrial Intelligence, or SETI, programs.

In 1961, Drake also outlined an equation to statistically compute the chance of extraterrestrial civilisations existing in the Milky Way. By assigning speculative numbers to things like the number of stars and planets in our neighbourhood of space, the likelihood that these would host life, and that beings there would be sophisticated enough to communicate technologically, and for how long, he estimated that there may be between 1000 and 100,000,000 planets with contactable civilisations in the Milky Way. Astronomers have tried to pin down the numbers more tightly but the bottom line is that the odds are probably small. The fact that no-one has yet reached out to us seems to prove that point – until someone does.

Even so, the stakes are high and, as Wells warned, you don't want to be caught out. In 1971 NASA funded a study into building a vast radio telescope called Cyclops to track signals from nearby stars. The billion-dollar project didn't happen but the technological ideas that went into it spawned other projects for monitoring signals from space, including with the Allen Telescope Array at Hat Creek, California. In July 2015, the Breakthrough Listen project was funded at the University of California at Berkeley, to carry

out SETI observing campaigns at Green Bank Observatory in West Virginia and the Parkes Telescope in Australia. Even China's new giant radio dish, the Five-hundred-metre Aperture Spherical Telescope (FAST), includes a SETI goal. But the search for extraterrestrial life is also continuing apace off-planet.

Planetary probes

Out of the devastation and technical scramble of the Second World War came rockets – powerful ones, capable of flinging man-made probes into orbit. In July 1958, US President Eisenhower signed an Act creating NASA. Amongst its specified tasks: expansion of human knowledge of phenomena in the atmosphere and space; improvement of the usefulness, performance, speed, safety and efficiency of aeronautical and space vehicles; plus long-range studies of the potential benefits to be gained from, the opportunities for, and the problems involved in the utilisation of aeronautical and space activities for peaceful and scientific purposes.

In 1960, NASA took a decision to name its planetary missions after nautical terms to convey 'the impression of travel to great distances and remote lands'. Thus, the first series of missions were called Pioneer, Mariner, Ranger, Surveyor and Viking.

Mariner spacecraft set many records. In 1962 NASA's Mariner 2 flew past Venus, and in 1965 Mariner 4 took the first close look at Mars, returning photographs and scientific data. Mariner 9 entered orbit around Mars in 1971 – the first artificial satellite to circle another planet – from where it photographed the Martian moons and mapped the red

planet and its weather. In 1974, Mariner 10 made it to Mercury, marking the first visit to that planet.

What did they find? Not always what they expected. Here's how we came to know more about the other rocky planets of our solar system, and then those farther afield.

Much the same size as the Earth, Venus is often considered our sister planet. But its clouds are not a feathery veil like those on Earth: they are dense and completely obscure the planet's surface. For hundreds of years, until as late as the 1950s, people assumed that Venus was a warmer version of Earth. In the middle of the nineteenth century, astronomical observations seemed to show that Venus's atmosphere was chemically similar to that of Earth, fueling expectations that forms of life might also exist there.

Science-fiction writers imagined it was just as habitable as Earth. Edgar Rice Burroughs depicted the planet as being much like the prehistoric Earth, complete with volcanoes, deserts, jungles and dinosaurs. In the short story *All Summer in a Day*, Ray Bradbury imagined the planet being continually drenched in rains: 'the drum and gush of water, with the sweet crystal fall of showers and the concussion of storms so heavy they were tidal waves'. A more dystopian depiction of Venus came in 1951 with Stanislaw Lem's book *The Astronauts*. In it, the planet was destroyed by a prior civilisation that had committed nuclear suicide.

When space missions reached Venus (Mariner 2 in 1962 and the Soviet Venera 7 lander in 1970) what they found was more like Lem's hell than Bradbury's drenched rainforests. Venus suffers from a runaway greenhouse effect. Its atmosphere is 96 per cent carbon dioxide, which traps the Sun's heat, making it the hottest planet in the solar system. Its surface, covered in black, slate-like rocks,

is baked to almost 500 degrees Celsius – enough to melt lead. Air pressure on Venus is more than ninety times that on Earth's surface, or equivalent to that 900 metres under the sea. Low volcanoes spew sulphurous gases into the Venusian atmosphere, where they form clouds of sulphuric acid. Lightning crackles overhead. Venturing there would be like stepping into a caustic furnace.

Recent missions to Venus, including Magellan (launched in 1989) and Venus Express (in 2005), have mapped its surface. It is covered with vast pancake-like volcanic domes and fresh lava flows, reminiscent of those on the Big Island of Hawaii. Venus rotates on its axis very slowly and in the opposite direction to the Earth and most other planets in the solar system. The reason is unclear, but space scientists suspect that it may have received a knock from a passing body long ago that altered how it spins. Therefore, a day on Venus is longer than its year and – if you could see it through the clouds – the Sun would rise in the west and set in the east.

Although Venus is far from the seductive destination promised by its namesake Roman goddess – associated with love, beauty, desire, sex, fertility, prosperity and victory – most features in the Venusian landscape have been named after women, real and mythical. Valleys are named after river goddesses or alternative names for Venus in languages from Mayan to Polish to Zulu. One mountain range is named after Aphrodite, the equivalent Greek goddess. Famous real women have their Venusian heartlands too, from nineteenth-century English palaeontologist and fossil-collector Mary Anning to twentieth-century American actor and singer Judy Garland.

As well as displacing Earth from the centre of the solar system, through Galileo's observations of this planet's

phases, Venus has also been instrumental in setting the scale of the inner solar system, through measurements of it moving across the Sun's face. In the seventeenth and eighteenth centuries, astronomers including Johannes Kepler and physicists like Isaac Newton had worked out the distances of many planets to the Sun, including Venus, but that to Earth was harder to evaluate: because we are on it, we cannot observe its motion from afar. They worked out that if you know Venus's distance from the Sun, and how long it takes to travel across the face of the Sun, then by triangulation – making several observations at slightly different bearings – you can work out Earth's distance too.

Such 'transits' of Venus only happen roughly every 240 years, as Venus's orbit doesn't always quite line up with the Sun as viewed from Earth. From the sixteenth century on, western scientists and explorers have sailed feverishly around the world – from the Arctic to South America and the South Pacific – to measure one of these rare events simultaneously from many places. For example, on the way to the east coast of Australia, Captain James Cook stopped in Tahiti to measure a transit in 1768, from a point on the island that is still called Point Venus.

Although post-1970s science-fiction writers had to change their tune after space-craft visited there and found a scorched barren planet, they didn't give up. Some imagined floating Venusian cities in balloons filled with oxygen and nitrogen. Apparently, anywhere can be made habitable. And recently some planetary scientists, too, have argued that Venus, like Mars, might have been more Earth-like in its past. It too might have once hosted oceans, which boiled away as the planet heated up – another salutary lesson to us as we experience human-made climate change on Earth.

Even closer to the Sun lies the smallest of the planets, Mercury. Unlike Venus, Mercury was long understood to be an extreme environment: tidally locked to the Sun, as the Moon is to Earth, with one face constantly scorched and the other in perpetual night. Writers mused on the possibility of living along the edge of its dark side, in continual dusk but safe from frying or freezing. But recent studies show that in fact Mercury does rotate slowly (three times for every two orbits), so its whole surface is gradually exposed to extreme solar radiation.

Two missions have visited Mercury: NASA's Mariner 10 (launched in 1973) and Messenger (launched in 2004). A third is on its way: at the time of writing, the European Space Agency and Japan's joint mission BepiColombo (launched in 2018) has made several flybys of the tiny planet and is posed for a close look in 2026. Mariner 10 was the first to use a 'gravitational slingshot' – gaining energy by first passing Venus, a bit like gaining speed on a swing – to get there. Mercury, it emerged, looks much like the Moon. It has no atmosphere to hold in heat so flips from being a frigid minus 170 to a scorching plus 430 degrees Celsius.

Mercury is named for its speed. The fastest travelling planet on the sky – it goes round the Sun every eighty-eight days – it is named after the Roman messenger god. Ancient Assyrian cuneiform tablets dating back to the fourteenth century BCE also designated Mercury 'the jumping planet'. Telescopes in the seventeenth century revealed that Mercury has phases, like Venus, and so must also orbit the Sun closer than Earth. It, too, is visible in the morning and evening.

Revealing Mars

On Mars too, the arrival of space probes (Mariner and Viking) in the 1960s and 1970s dashed hopes of intelligent life. In 1965, NASA's Mariner 4 became the first spacecraft to reach the red planet, following several failed attempts by the Soviet Union. Within a few years, Mariner 6 and Mariner 7 also both made it. Each sent back dozens of photos, showing a landscape pockmarked with craters, appearing much like our Moon. Soviet probes arrived in 1971, when craft called Mars 2 and Mars 3 entered orbit. The latter released a lander – technically the first craft to land softly on another planet, even though it only worked for a few seconds before failing.

NASA's Mariner 9 was close on their heels and snapped more than 7000 photographs over a year. These were more surprising. When the probe arrived, the scientists were greeted with a blank slate. The whole Martian surface was obscured by what appeared to be a vast cloud of dust and no features at all were visible. The storm raged for a month, then gradually the haze began to clear. To the watching scientists' amazement, a shape began to emerge from the fog – a colossal conical peak, looking much like the top of a volcano. It was just that – the summit of Olympus Mons, the biggest mountain in the solar system, now dormant.

As the dust settled more, a vast warren of gorges appeared near the Martian equator. Now called the Valles Marineris, after Mariner, these canyonlands stretch for thousands of kilometres; the deepest scar plunges seven kilometres below the surface. These Martian ravines are far deeper and longer than the Grand Canyon on Earth, which is about 800 kilometres long and two kilometres deep.

This was a completely new view of Mars. The red planet's landscape suddenly looked a lot more like Earth than the Moon. Interest was piqued, and more spacecraft were hurled

in Mars's direction. In 1976 two US orbiters, Viking 1 and 2, arrived at the red planet and dropped landers capable of performing geological analyses. These showed that Martian rocks were very similar in composition to some meteorites found on Earth – so similar in terms of minerals, crystal structures and trapped gases that scientists assumed these 200 or so unusual terrestrial meteorites must have originally come from Mars. Perhaps they were cast out by asteroid strikes and sent whirling through the solar system only to crash to Earth in a brief fireball. It also turned out that the reverse was true: some Martian material was already present on Earth.

The hunt for similarities picked up pace. In 1997, NASA's Mars Global Surveyor began to map the planet from pole to pole, revealing signs that there may have once been liquid water on the surface. It found gullies that looked like they had been once carved by streams and minerals like hematite that form in water. The Pathfinder lander and Sojourner rover also arrived that year and became the first to touch down using airbags to cushion the landing and to roam about the surface, respectively. Each lasted just a few months before communications were lost.

The 2000s saw more probes, landers and rovers, some of which operated for years – a few are still going. Since 2001, NASA's Mars Odyssey has returned more than one million images of the planet and maps of certain chemical elements within its rocks and soils. Mars Express, launched by the European Space Agency (ESA) in 2003, mapped the geology in more detail. It also carried a lander, called Beagle 2.

Built by British scientists, Beagle 2 was named after HMS Beagle, the ship that carried English naturalist Charles Darwin around the world in the 1830s – voyages to places like the Galapagos Islands that led Darwin to the theory of

evolution by natural selection. The charismatic leader of the Martian lander project, Colin Pillinger, hoped that their vehicle would make discoveries of equal importance off Earth, by searching for signatures of past life on Mars.

Beagle 2 was also a cultural emissary. It carried the first piece of Earth art to Mars – a ‘spot painting’ by British artist Damien Hirst. This painting comprised sixteen circular spots, each made with a different natural pigment, chosen to mirror the colours of minerals found on Mars – such as iron oxides (reds and browns), iron silicates (green), copper carbonate (blue) and titanium oxide (white). Set on an aluminium plate eight centimetres across, the spots weren’t just decoration. They were intended to be used for calibrating instruments on the lander, such as focusing the microscope, as well as matching the colours of the Martian landscape to known ones on Earth for interpreting photographs.

Unfortunately for these scientists and the artist, contact with Beagle 2 was lost during descent. The lander was eventually spotted years later from the skies by a subsequent orbiter: it had made it to the planet but had then failed to deploy properly. All the same, the extraterrestrial artwork lives on, upon Martian terrain.

Where Beagle 2 failed, NASA rovers Spirit and Opportunity succeeded in reaching the surface intact in 2004. They spotted rounded pebbles and layered sediments, consistent with the presence of water in the past. Eventually each fell silent – Spirit in a sand dune in 2010 and Opportunity during a sandstorm in 2018. Two more landers, Mars Phoenix and the Curiosity rover, have found more evidence of past water as well as the presence of methane and other carbon-rich compounds. In its most basic sense, water and carbon chemistry are conducive to life, even if no direct evidence

for any organism, alive or dead, has been found on Mars to date.

Further missions from the US, India, Europe and Russia have continued to map Mars's surface, geology and atmosphere in exquisite detail. Mars now even has its own Google Map. Scientists have also managed to learn, by analysing earthquake shudders, that Mars has a molten core, like the Earth's, and a thinner crust than our planet (just twelve kilometres deep, compared to Earth's 5-70 kilometres). Mars has no tectonic plates, though: its rocks crack and shift as the planet slowly cools and shrinks.

Mars's diameter is about half that of Earth, and about twice that of our Moon. It has lower gravity – if you stepped on Martian soil you would weigh around one-third of what you would on our planet. Being farther away from the Sun than Earth is, on average Mars is a chilly minus 63 degrees Celsius, compared with Earth's average of 14 degrees. A Martian year is twice as long as ours, although one Martian day is much the same: twenty-four hours and forty minutes. Mars has precious little air around it, and what is there is nothing like Earth's, which is mainly nitrogen (78 per cent) and oxygen (21 per cent). Mars' is mainly made of carbon dioxide (96 per cent), plus smatterings of nitrogen and argon, and a little water vapour.

The two most striking features of Mars, as seen through a telescope, are its white polar caps, which wax and wane with the seasons. They are mostly made of water ice, topped with solid carbon dioxide ('dry ice'), which is deposited in the Martian winter. Winds carve out vast spiralling forms, grooves and pits in the ice caps. Fine, dark spidery features appear in spring, etched by escaping gases and dust as the ice warms.

Elsewhere, the red planet's hemispheres differ markedly. The southern side of the planet is elevated and peppered with the cones of extinct volcanoes. Most of the northern side comprises low-lying plains. Scientists don't know what caused these great geological contrasts, but they think they must have been set up long ago, when the planet was still young. Perhaps magma flowed unevenly beneath the surface, or another celestial body collided with Mars, knocking off mountain crests on one side.

There are no seas, rivers or lakes on the Martian surface today, although radar observations hint that there may be a pool of liquid water locked beneath icy deposits at the south pole. Even if liquid water did seep up from below, once on the surface it would soon evaporate off into space given the slow burn of ultraviolet light from the Sun and the lack of a containing atmosphere.

Yet scientists think that Mars might have been wetter in the past, perhaps as far back as 4 billion years ago – half a billion years after all the planets in our solar system condensed out of a primordial ring of gas, rock and dust encircling the Sun. Minerals that form in water, like hematite and jarosite, are present on Mars. The shapes of some craters hint that the ground was wet at the time a particular asteroid hit. And white streaks that look like trickles of water appearing and disappearing on the sides of cliffs have been seen from orbiting spacecraft, though the exact nature of these remains unexplained.

Mars may have once had a thicker atmosphere too. When they were active, Mars' volcanoes would have given off a lot of gases. Blanketed by carbon dioxide, which traps heat, young Mars might have experienced a 'greenhouse effect', making the planet warmer as well, and a lot more like Earth today.

Geologically, many Martian features mirror ones found on Earth. There are many dormant volcanoes, including the immense Olympus Mons, which is twenty-two kilometres high, or about two and a half times the height of Mount Everest. A squat 'shield volcano', like those in Hawaii, Olympus Mons has a shallow cone and is extremely wide at its base, which spans 600 kilometres. Standing on Mars at the foot of Olympus Mons, the peak of this former volcano would be so far away it would lie beyond the horizon.

Sand dunes are also common on Mars, as are layered deposits of sediments. Most Martian rocks are igneous - of volcanic origin - such as basalts. But there are also other familiar forms, such as sandstones and mudstones. The minerals found there are familiar too: olivine, pyroxene, feldspar, carbonates, sulfates, silica and iron oxides like hematite. Mars retains more craters on its surface than Earth, where they have been largely lost through weathering and recycling of crust through plate tectonics.

Mars has seasons, as the axis on which it spins is tilted, like Earth's. But its weather patterns change little from year to year, as without the annual swings of unfurling and dying vegetation, the surface stays much the same. There's no rain, though some landers have spied snow showers high in the atmosphere, flakes from which never reach the ground. Wispy clouds, seeded by dust particles, have been caught drifting past by rover cameras.

Fierce winds often whip around the planet, with gusts reaching near hurricane speeds of around one hundred kilometres an hour. These churn up dust that swirls and spreads, ranging from small dust devils, which rovers have filmed rushing across plains, to planet-wide storms, like the one experienced by Mariner 9. These storms can last for weeks because Mars is so dry. Streams of particles given off

by the Sun, called the solar wind, also blast the planet, which has no magnetic field to deflect it, and may be one reason why so little atmosphere remains.

All this dust is also why Mars looks red. Many Martian rocks contain iron, which turns to iron oxide or rust when exposed. Seen from space, the planet as a whole looks reddish, and from its surface the sky is pink. But there are many other colours on the planet. As on Earth, Martian rocks have many hues, from browns and greys to greens – like Damien Hirst's spots on Beagle 2.

What would it be like to walk across the Martian landscape? Probably much like being in a cold, dry desert on Earth, such as the Atacama in South America, but set against peachier skies. Being lighter in weight, you might bound easily across the ground, dodging whirling dust devils and fierce reedy winds.

You would also notice the utter silence.

Microphones on the Perseverance rover have captured the faint sounds of Mars, including the soft rush of breezes alongside the whine of its motors, creaking wheels, zaps of lasers and puffs and pings of tools. But acoustic emptiness prevails. 'We thought the microphone was broken, it was so quiet,' one NASA scientist remarked on hearing the first recordings.

But listen closer and the quality of Martian acoustics are very odd. Sounds don't carry far – typically eight metres compared with sixty or so on Earth. It's like being in a sound-deadened room. And high-pitch sounds hardly carry at all.

In the Martian recordings you can hear a very low hiss and rumble from the microphones being buffeted by wind, with high-pitched creaks from the rover sounding faint as if they are very far away. Acoustics might also change with the

seasons, as air pressure varies through the year. While there's much to recognise, it is still an alien place.

Perseverance's job on the red planet is to fill tubes with samples of Martian rocks, soil and air. It is a mobile laboratory, a robot geologist on wheels, bristling with high-tech kit: cameras, a radar, weather station and lasers that blast rocks to reveal their chemistry. By extending a two-metre-long robotic arm, Perseverance can grab or examine rocks and soils up close. It can drill out cylindrical samples of rock, around the size of a small battery, and store them in tubes that it then seals and holds within its belly.

Clutches of these tubes are deposited on the surface to be picked up by a later mission: hopefully in a decade or so, if budgets allow. If all goes according to plan – and it is quite a plan, involving landers, mini-helicopters and rockets to collect the tubes and launch them back to an orbiter to propel them back to Earth – Perseverance's hard-won and highly prized samples might be returned sometime in the 2030s.

Just as the rocks returned by the Apollo astronauts from the lunar surface hold vital clues about the origins of the Moon and our own planet, scientists are impatient to pore over Perseverance's suite of samples. But while the minerals and gases within the tubes will tell us what Mars is made of and offer clues on how they may have been formed, the answers within will also be fodder for designing future human trips to Mars. The rover has already trialled a system on the red planet for extracting oxygen chemically from the Martian atmosphere. Future astronauts may need similar means to make oxygen for breathing or to prepare rocket fuel to get home.

With so much at stake, scientists chose the site for Perseverance's touchdown very carefully. They selected a

location that might also potentially tell us something about key ingredients for sustaining life beyond Earth. Water is one, and Jezero Crater, a 45-kilometre-wide depression just north of the Martian equator, is thought to be the remnant of an ancient lake and river delta that dried up millions of years ago. (Jezero means 'lake' in Slavic languages.) When the solar system was very young, some 3.8 billion years ago, space scientists speculate that Mars might have had water on its surface, much like Earth. Lakes like the one in Jezero might even have hosted forms of life - although we've no idea of what kind, or conversely, whether Mars has been truly barren throughout its history. Whatever turns out to be the case, scientists are keen to check Jezero out.

Many countries are getting in on the act. When Perseverance blasted off in July 2020, it was accompanied by two other spacecraft, all taking advantage of a periodic alignment between the orbits of Earth and Mars, meaning that craft could travel there quickly using minimal fuel. China launched Tianwen-1 ('quest for heavenly truth'), a more far-flung space probe after a series of successful lunar missions. The package contained an orbiter, lander and a rover called Zhurong, to survey the planet's atmosphere and interior as well as its surface. The United Arab Emirates, meanwhile, launched Hope, an orbiter to produce a global weather map of Mars, and the first probe by a West Asian, Arab or Muslim-majority nation. The government used the mission to mark the nation's fiftieth anniversary in 2021, to inspire the young and boost the country's tech sector.

The planet's allure still holds as somewhere that might host at least remnants of life. But, scientifically, as ever more craft probe the red planet, breakthroughs are proving difficult. A little water may be present, but not enough to satisfy organisms' thirst. A whiff of methane might be

detected, but not so much that it gives away the presence of microbes. The greatest secrets of the planet's history may lie too far beneath its surface to gather with rovers that just scratch the dirt or satellites flying above. For space scientists, the frontier of habitability has moved on, to more distant icy worlds.

Outer solar system

As the Moon, Mercury, Mars and Venus have turned out to be more sterile than we had hoped, our attention is now moving outwards to more extreme places to search for clues that might tell us where we came from. The outer solar system is a time capsule of our history. Reservoirs of gas, rock and dust out of which the planets formed are suspended here in a deep freeze.

Saturn and Jupiter are the main characters. Both planets have been known since ancient times, as they are visible with the naked eye. Jupiter is the largest planet in the solar system and is named after the Roman god; Zeus was his equivalent in ancient Greece. Astrologically, Jupiter is associated with 'joviality' - merry or happy moods, whereas Saturn is more down to earth, and named after the Roman god of agriculture, Saturnus (equivalent to the Greek god Cronus or Kronos). To the Chinese, Jupiter is the 'wood star' and Saturn the 'earth star', each one of the five elements.

Uranus and Neptune are also named after gods - Uranus after the Greek god of the heavens and sky (known to the Romans as Caelus), and Neptune after the Roman god of the sea (to the Greeks, Poseidon). Neither planet is visible to the naked eye and both were discovered relatively late, through a telescope. In 1781, English astronomer William Herschel spotted Uranus moving through the field of stars: in 1846,

Neptune was found at a position where it had been predicted mathematically, explaining unusual aspects of Uranus's motion. It then took more than a century more to get to know these planets.

In the mid-1960s NASA engineers realised that they had a once in a lifetime chance – to take advantage of a rare alignment of Jupiter, Saturn, Uranus and Neptune that occurs every 176 years and send a spacecraft to all four outer planets in one mission. If launched in the late 1970s., the spacecraft would be able to fly close to each planet and could borrow a bit of gravitational energy to slingshot it on to the next, just as a skateboarder builds up speed rolling down a ramp to take it back up another.

Engineers set about designing two craft to do it, which were adapted from the Mariner probes, and they named the project Voyager. Voyager 2 was launched first, in August 1977. It would take a slightly slower route than the next probe, Voyager 1, which was lofted in September of that year. It was set to be a busy decade for planetary scientists and members of the public alike. And I wonder if it is this ambitious mission, in particular, that impelled me most of all to become an astronomer, my own horizons stretching alongside those of knowledge about our neighbouring worlds as the probes made regular headlines for years.

In March 1979, Voyager 1 reached Jupiter. People around the world – me included – watched on their televisions with rapt attention as its cameras revealed the swirling clouds of the Great Red Spot – a huge hurricane-like vortex – and caught flashes of lightning in the Jovian atmosphere. The probe went on to fly past several of Jupiter's moons, spying grooves on the surface of Ganymede that suggested that past forces may have broken up and shifted parts of the surface. It witnessed volcanic activity on Io – the first seen

in the solar system beyond Earth. A stream of charged particles was being ripped off that moon and being sucked towards Jupiter, to reinforce a belt of strong magnetic field around the planet. Voyager 1 also captured images of faint rings around Jupiter and discovered two small new moons, Thebe and Metis. Not bad for one plucky spacecraft. And the public didn't have to wait long for more.

Reaching the giant planet a few months later in July, Voyager 2 scrutinised these rings further and spied a third new Jovian satellite, Adrastea. It revisited Io's volcanoes, finding that while some had stopped, several were still erupting, suggesting they did so for months at a time.

Just over a year later, Voyager 1 reached Saturn and its even more spectacular ring system, again to great fanfare on television. At close quarters, the rings were thin, not a solid plane but split into many finer hoops or ringlets. Some regions were warped or had kinks and a series of broad bright 'spokes' stretched across the whole ring system radiating out from the planet. The probe discovered more moons (Atlas, Prometheus and Pandora), some of which sat within gaps in the rings. The scientists concluded that small moons must play a role in clearing and shepherding the myriad icy blocks that make up Saturn's rings.

Voyager 1 photographed the moon Enceladus, finding it unusually bright and reflective, its surface like fresh crisp snow. Saturn's biggest moon, Titan, was also a surprise - shrouded in a thick, nitrogen-rich atmosphere, chemically similar to Earth's but denser and tinted burnt orange by carbon-rich chemical compounds. Such chemistry hinted that pools of liquid hydrocarbons such as methane might well lie on the surface.

After this revelatory splash, Voyager 1 took a bow as it had completed its planetary mission. The little probe tilted

and turned to fly off, out of the plane of the solar system.

Its sister craft, Voyager 2, reached Saturn in August 1981, photographing more of the icy moons, and detecting a vast hexagonal weather feature at one pole. Then it whizzed off and went quiet for a few years, until in January 1986 it encountered Uranus. That planet was more muted – a duck-egg-blue featureless ball. But it wasn't alone: a dozen moons and dark rings were spotted circling it. There were other striking features, too: the planet's magnetic field was at an odd tilt, more closely aligned with its equator than its rotational pole. And it was really in the deep chill of space – Voyager 2 detected temperatures as low as minus 214 degrees Celsius, making it the coldest planet in the solar system.

Voyager 2 was now so far away that its radio signals were becoming feeble. NASA extended the size of its suite of radio dishes around the world to make its deep-space communications more sensitive, so that it could pick up messages from Voyager 2's next destination, Neptune.

The spacecraft arrived there in August 1989, photographing more moons and faint rings around the sky-blue planet, flecked by white streaks of cloud. Neptune also had a giant storm whirling in its atmosphere, named the Great Dark Spot. One of its moons, Triton, exhibited a fractured terrain reminiscent of the brown webbed patterning of a cantaloupe melon rind. Geysers erupted from pink ice at one of the moon's polar caps.

Later that year, its tour of planets completed, engineers turned off Voyager 2's cameras to conserve power, but they kept communications open, along with instruments for taking measurements of the solar wind, the flow of particles off the Sun that pervades the solar system. Voyager 2

trundled off into the black abyss of space, sailing along its gravitationally determined path like a mechanical comet.

But on 14 February 1990, Valentine's Day, Voyager 1 was woken up. It sent back one final postcard before its systems too were put in sleep mode. Some 6 billion kilometres from the Sun, it took a 'solar system family portrait', showing Venus, Earth, Jupiter, Saturn, Uranus, Neptune and the Sun, all in one shot taken from the edge of the solar system. The planets are just visible against the background stars.

In this photograph, Earth is merely a 'pale blue dot' in space, as astronomer Carl Sagan poignantly described it. That dot is our fragile home. While the Apollo astronauts' snaps of Earth from the Moon showed it as a planet of green-ochre contents and glinting seas, brimming with life, Voyager's more minimalist portrait is more challenging. All that detail is washed out into a single hue representing the ocean and sky. Humans and all living things on this planet we hold most dear are inconsequential in the vast darkness of space. From afar, even a jewel of a planet appears a rather dull spectacle amongst the shining stars.

The golden record

As engineers and scientists planned the grand tours of these early spacecraft, the legacy of these missions was also in their minds. With *Star Trek* on television and science-fiction novels in bookstores, some of them imagined that their machines might one day end up in the hands of distant spacefarers, whether our future selves or some other beings. How would those off-planet 'archaeologists' make sense of them?

A few years before the Voyagers left, NASA had launched two earlier twin probes, Pioneer 10 and 11, to the outer

solar system. Pioneer 10 went first. It left Earth in 1972 and managed to cross the belt of tumbling asteroids between Mars and Jupiter – a swathe of objects ranging in size from dust particles to rocks as big as Alaska – to become the first probe to reach Jupiter in 1973. Pioneer 11 followed one year later and became the first spacecraft to reach Saturn in 1979.

Each of the Pioneers carried an aluminium gold-plated plaque with a pictorial representation of two human naked figures, male and female, a sketch of where Earth is relative to the other solar system planets, and a drawing pinpointing the Sun's location relative to fourteen stars. These stars are pulsars, which are spinning dying stars that send out characteristic regular bleeps of radio waves, and so would be easy to recognise.

The idea to attach an extraterrestrial message to the Pioneer probes is credited to a British science journalist, Eric Burgess, who approached US astronomer Carl Sagan following lectures he'd given on communication with intelligent extraterrestrials. Sagan persuaded NASA, and within weeks he had designed and sketched the plaque with his colleague Frank Drake (of Drake's Equation), Sagan's wife Linda and the American space artist and journalist Jon Lomberg.

NASA took the idea a step further with the Voyagers, attaching to each of them a phonograph record – a thirty-centimetre diameter gold-plated copper disk charged with sounds and photographs from diverse cultures on Earth. All the details are there to help the finder play it, from instructions in binary arithmetic (0s and 1s) about the correct rotational speed to play the record (relative to the precise universal timescale of a key energy transition of a hydrogen atom) to sketches of how to deploy the stylus

needle attached. Other sketches explain how to build up photographs from the signals within the record, by stacking up lines of data to render pictures. The first image is a circle, to act as a check that they are doing it correctly.

The pulsar map from the Pioneers' plaque is included too, to indicate where the probe came from. And a spot of uranium is deposited on the aluminium cover to help the finders work out a timescale from the rate of its radioactive decay. They have a long time to do it; half of the uranium atoms will decay (by emitting particles to become a different element) in 4.5 billion years. The inscription 'to the makers of music - all worlds, all times' is etched by hand on the records' surfaces.

Carl Sagan took the lead again in selecting what went on to the Voyager record. He assembled a committee with an unenviable task - to choose 115 images and a range of sounds to represent all the peoples of Earth. Some of the first images define numbers and units, such as the length of a second, day and year, the mass of a kilogram, and distances in metres or kilometres, which are then used to describe the sizes of the planets in the solar system. Photographs follow, of the rainbow spectrum of light, surface of the Moon, and images of Jupiter, Earth and clouds and oceans on Earth.

Next come chemical symbols, including of DNA, followed by sketches of a sperm and an egg, a human foetus, and male and female adult humans. There's a colour photo of a woman breastfeeding an infant, a silhouette of a family, differentiating a 4-year-old, 12-year-old, 30-year-and 80-year-old human. A map of Earth's continents is filed, and a photo of an island on the Great Barrier Reef. Pencil sketches convey animals and bushmen hunting them.

Then come colour photos of people from around the world: a man from Guatemala, a sprinter from the USSR, students and a teacher in a schoolroom, fishermen, people licking ice-creams, eating toast and drinking water. Voyager voyeurs can see thatched huts in Africa, a modern house in New Mexico and the towering United Nations building in New York. There are shots of cars, planes, a rocket launch and an astronaut.

Selected sounds include the rumble of volcanoes, earthquakes and thunder, plus the hiss, patter and smash of wind, rain and surf. Animal calls range from chirping crickets and barking frogs to laughing hyenas, chattering chimpanzees and groaning elephants. Human sounds are on there too, from a blacksmith hammering metal to a kiss, heartbeat and laughter.

Music also features, along with spoken greetings from people in fifty-five languages and printed messages from then-US President Jimmy Carter and then-UN Secretary General Kurt Waldheim. Passages include Bach's *Brandenburg Concertos*, Mozart's *Magic Flute* and Stravinsky's *Rite of Spring*. Javanese gamelan, Senegalese percussion and Peruvian pipes are highlighted, and the close harmonies of a Georgian choir. The project's American origins are evident in the inclusion of blues and rock and roll, such as 'Melancholy Blues' performed by Louis Armstrong, 'Johnny B. Goode' by Chuck Berry and, fittingly, 'Dark Was the Night' by Blind Willie Johnson.

Viewed today, these choices seem as limited as plots and characters from grainy television series of the time. What might alien intelligences make of them? Perhaps that Earth's a noisy planet with terrifying natural cataclysms, full of aggressive beasts and their discombobulating calls. Yet they might see that it is also communal – the animals sing

together, work collectively to build vast structures and to beat out rhythms. Underpinning all, the makers of these craft knew how to use the tools and materials that the Universe has bestowed, from mathematics to atoms. They, we, are creative creatures who want to forge, explore and exploit connections with the cosmos.

Water worlds

In the decade after the Voyagers' visits, further missions roared off to Jupiter and Saturn, to follow up on what they had seen. These gave us a far more detailed view of what the environs of these gas giant planets were like, including some more surprises.

The Galileo spacecraft arrived at Jupiter in 1995. It became the first probe to go into orbit around that planet, and hung around the gas giant for eight years, flying close to its clouds and weaving back and forth past its many moons.

About the size of a small car (5m long and weighing two tonnes), Galileo carried ten instruments, ranging from sensors for measuring magnetic fields and detecting high-energy particles and dust grains to cameras able to take images at different wavelengths and split the light into spectra for deducing the chemical make-up of the planet's atmosphere and moons. Galileo's cameras were able to take images hundreds of times sharper than those on the Voyagers.

Soon after the spacecraft arrived, it ejected a small probe into Jupiter's gas clouds. Protected by a heatshield capable of withstanding temperatures of 16,000 degrees Celsius, and slowed by a parachute to begin its descent, it sent back data for an hour and travelled almost 200 kilometres into

the clouds before its signal got cut off and it fell to its destruction somewhere below, crushed and boiled by the huge pressures and surging vortices of the planet.

The probe detected that Jupiter's atmosphere was mostly made of hydrogen. But it was also flushed with more heavy elements than the Sun - three times as much nitrogen, carbon and sulphur and noble gases such as argon and xenon, perhaps having come from other bodies falling in. It measured vast thunderstorms and wind speeds as strong as 600 kilometres per hour, suggesting that the turbulent gases were stirred by powerful internal sources of heat. There was little lightning or water vapour though, posing questions for the origin of water on Earth - presumably it was not carried from material such as that that makes up the Jovian clouds.

Galileo passed by Jupiter's major moons as well. It revisited Io's volcanoes, finding that they are driven by tides on the Moon. The gravitational tug of its vast neighbour Jupiter causes the moon to bulge, with the bulge changing shape as the moon orbits Jupiter on an elliptical path, stirring its inside, to create heat by friction. Io is the most volcanically active body in the solar system, its surface is being constantly re-clad with lava and by plumes of gas and rock in an ever-changing patchwork of red, black and white marks. If not for this internal stirring, Io would probably look a lot like our Moon, inert, pockmarked by impacts and geologically dead.

Another Jovian moon, Europa, couldn't look more different. Its dusty white and beige surface is incredibly smooth, flecked only with wispy pale striations. It is covered in water ice, and astronomers think that a similar mechanism of tidal heating to that on Io keeps an ocean of liquid water warm

beneath the frozen surface – which may contain more water than all of Earth's seas.

A small sub-surface ocean has also been suggested on Callisto, Jupiter's second largest moon. Its origins are quite different, though, and lie simply with the slow cooling of this big satellite after its formation (just as Earth's core remains hot today). Callisto's surface is far more like our Moon: grey, inert and cratered. Hints of such an ocean come from subtle magnetic signatures, which may originate in electric currents induced by Jupiter's strong magnetic field running through salty brines.

The solar system's largest moon, Ganymede, is twice the size of our Moon, larger than Mercury and three-quarters the size of Mars. It is also magnetically active, with its own field driven perhaps, like Earth's, by a still-molten core. This almost-planet appears to be a mix of rock and water ice and has two types of terrain on its surface: ancient dark regions pockmarked with craters, and paler zones with grooves and ridges thought to have been more recently resurfaced, although planetary scientists are unsure exactly how. Ganymede may also have a sub-surface ocean.

Given all this activity and the presence of liquid water, it's not much of a leap to wonder if primitive forms of life could exist within the oceans of Jupiter's moons. They have become the next key destinations for astrobiology research, after the inner rocky planets have failed to deliver.

Further spacecraft have and will be headed that way, including NASA's Juno probe, which arrived there in 2016 to follow up Galileo's discoveries. Galileo's mission was terminated in 2003, when it was deliberately sent spinning in towards Jupiter and burned up in the atmosphere.

Similarly exciting explorations have also taken place at Saturn, through the Cassini spacecraft – a joint endeavour of

NASA, the European Space Agency, and the Italian space agency, named after the seventeenth-century Italian astronomer Giovanni Domenico Cassini who observed Saturn and found a dark gap in its rings. The Cassini mission studied Saturn from 2004 until 2017, when it too was sent spiralling into the clouds of the vast distant planet it had spent years deciphering. Some of the places found in the Saturnian system are just as unusual as those around Jupiter. Some are even more enigmatic.

Saturn itself remains mysterious. The second largest planet in our solar system, after Jupiter, its diameter is nine times that of Earth. Like Jupiter, it is mostly made of gas, especially hydrogen and helium. It's not known if it has a solid core, but the outer regions rotate quickly, every eleven hours or so, and the planet takes twenty-nine years to go once around the Sun.

Saturn's largest moon, and the solar system's second largest, is named Titan after the Greek gods who ruled the cosmos. It's the only moon in the solar system with a thick atmosphere. The Cassini spacecraft carried a lander destined for there, called Huygens (named after Christiaan Huygens, who also avidly studied Saturn). In January 2005 it descended to the surface of Titan – becoming the first probe to land in the outer solar system.

Slowed by parachutes, Huygens plunged through the orange-brown clouds and held on against hectic winds. Tens of kilometres above the surface, it sent back images of the terrain – not a cratered or volcanic place but one riddled with branched channels, looking much like rivers running into an estuary or delta on Earth. More parachutes deployed and the probe plopped down – thankfully, onto hard material. Astronomers had had no way to know if it would be solid or liquid. The dust cleared, to show a landscape

strewn with flat icy pebbles in a sepia haze. A dry lakebed perhaps? More data from Cassini proceeded to reveal lakes and seas on Titan as well as long, wind-blown sand dunes.

Despite such Earthly similarities, to our eyes, Titan is not a welcoming place. The temperature there is a numbing minus 180 degrees Celsius and the nitrogen and methane in the air react to make a chemical smog, which is what gives the planet its orange haze and withers the weak light from the Sun to permanent dusk. Titan's lakes and seas are filled not with water but with liquid methane. And its dunes are rolling masses of solid hydrocarbons precipitated out of the atmosphere, hundreds of kilometres long and around one hundred metres high.

Saturn's other moons may be more hospitable to some forms of life, much like Jupiter's. Enceladus is one of the most dramatic. This tiny moon, a mere 500 kilometres in diameter – small enough to fit within the length of the UK – was known to be unusually white and bright – only water ice is that reflective. But as Cassini flew past, it noticed some unusual features.

Near the south pole of Enceladus was a series of parallel darkened cracks, which the scientists dubbed 'tiger stripes'. The region otherwise looked relatively young – the surface was pristine and didn't have any craters on it from collisions with space rocks. It had some ice boulders the sizes of houses plonked around, and there was something funny about its local magnetic field.

Cassini provided further clues, first by detecting a vast plume of water ice being vented out from the tiger stripes, and then finding that the south pole was warmer than it should be. The tiger stripe region was tens of degrees Celsius warmer than the equator of Enceladus. Something was certainly going on.

The reservoir of liquid water that was being sprayed out in giant geysers had to be close to the surface. Astronomers sent Cassini on ever closer flybys, to within 200 km of the ice, to see more. Cassini's detectors spotted a host of chemistry: carbon-rich compounds including carbon dioxide, carbon monoxide, methane and ammonia, as well as silica and phosphorus, and potassium and sodium salts (as found in our seawater).

Eventually they came to one conclusion: Enceladus too must have a sub-surface ocean of liquid water, covering the whole moon. Again, tidal frictions were heating up parts of the body, forcing the liquid water to the surface, where it sprayed out from the 300-metre-deep tiger stripe cracks, to fall back as fresh snow around the vents. Enceladus, like Europa, must be a water world, and has been added to the list of top destinations for future searches for extraterrestrial life. Cassini had become the first mission to sample the chemistry of such a distant ocean.

All these spacecraft showed that Jupiter and Saturn, despite being so captivating to look at, are essentially bleak, violent places. They are riven with enormous storms, whistling magnetic fields and lightning. Yet all this turmoil also energises their frozen moons. Blisters of liquid water emerge from the deep freeze, and geysers of steam erupt.

Missions are being planned to tap these sub-surface oceans, which may be capable of hosting life, just as deep ocean vents on Earth sustain microbes and crustaceans. Once they get there, reactions to what they find could be profound. Discovering extraterrestrial life would mark another great downsizing and humbling of the human psyche. But what will it mean if these distant pools turn out to be sterile too? Where will we look next for our origins? We are confident we can understand these places – the laws of

physics are evident, for example, in the coordinated spinning of Saturn's rings or in Jupiter's cyclonic red spot. But just like scuba-diving off the edge of a coral reef into the dark blue abyss below, there's a lot that is hidden, especially in the gloom at the solar system's edge.

Frozen edge

Uranus and Neptune and their systems of rings and moons have yet to receive robotic guests. All that we know about them has been gleaned from Voyager flybys and observations using telescopes. But one still more distant location has had a recent visit – Pluto.

After shooting past Jupiter in 2007, NASA's New Horizons probe whizzed past this distant world at the solar system's edge in 2015. One goal of the mission was simply to measure the diameter of Pluto, which was put at 2370 km, or roughly the distance from London to Athens: small, but a bit larger than expected.

Scientists were surprised though by how spherical Pluto was. Before the craft went there they had assumed that, because it was so small, it wasn't a real planet at all but an icy body that had been captured into orbit around the Sun. They expected it to look lumpy, more like a potato than a tennis ball. Indeed in 2006, the International Astronomical Union (IAU), astronomers' global professional body, debated whether to demote Pluto from the list of solar-system planets, and members voted to do so. Pluto went from being 'ninth planet' to merely a 'dwarf planet' alongside large asteroids like Ceres.

The IAU specified that a bona fide planet should fulfil three criteria: it must orbit the Sun, be massive enough that its shape is controlled by gravity and thus is near-round, and

its gravity must be big enough to have swept up other objects (other than moons) in its orbit. Pluto fails on the last count: it sits within a distant ring of small icy objects in the outer solar system beyond Neptune – in a region known as the Kuiper Belt, after Dutch astronomer Gerard Kuiper who suggested the belt's existence in 1951.

Many comets spend much of their time here, crawling through the inky darkness on the outer parts of their elliptical orbits before they briefly speed back inward to flare and shine as they pass the Sun. We cannot see these 'dirty snowballs' except in reflected sunlight and we only notice them when they swoop in towards the Sun. Their sudden appearance can surprise. For example, William the Conqueror delayed his invasion of England in 1066 when a comet was sighted, as the Bayeux tapestry records. Istanbul's observatory was torn down in the sixteenth century after the sultan's astronomer Taqi ad-Din misread a comet's omen: rather than the military success he forecast, a plague followed.

In any case, New Horizons scientists had low expectations of Pluto, and what the probe found came as a surprise. Not only was it very round: Pluto's surface was also smooth and scarred – looking more like a mash-up of some of Jupiter's and Saturn's active moons than a haphazard snowball or agglomeration of lumps of rock. It had a thin hazy atmosphere and a vast heart-shaped glacier of frozen nitrogen, 1000 kilometres across.

Pluto's geology suggests it may have had liquid on its surface in the past, and a thicker atmosphere than it does today. It also might have an ocean of liquid water beneath its frigid veneer. Pluto has its own companion moon, Charon; rifts on its surface also hint that it too might have hosted past subsurface seas.

After its encounter with Pluto, the New Horizons spacecraft kept ploughing on. And in 2019 it flew within 3500 kilometres of another icy body on the solar system outskirts, dubbed Arrokoth – the most distant body explored by a spacecraft to date. Just thirty-five kilometres across, it did turn out to have an unusual shape, like a fat, asymmetric dumbbell, with one lobe twice as big as the other. Space scientists scratched their heads; they'd seen nothing like it. There's still lots to learn at the solar system's edge.

In 2017, astronomers faced another conundrum. At a telescope in Hawaii, they spotted a small object that looked like an asteroid or comet, but that wasn't travelling in the way they expected. A cigar-shaped object, hundreds of metres long and reddish, it was travelling too fast to be following a typical elliptical orbit around the Sun. They deduced that it was going so fast that it would pass right through the solar system and must have come from beyond it. The astronomers named this first detected interstellar object 'Oumuamua, meaning 'first distant messenger' or 'scout' in the Hawaiian language.

'Oumuamua appears to have come from roughly the direction of the bright star Vega. This is close to the direction the Sun is moving in relative to the nearby stars, implying that the object may be a sort of cosmic driftwood, floating through space past us against our own motion. Its spaceship-like shape didn't stop some astronomers reaching again for the science-fiction books, however. And, just in case, the dishes of the Green Bank radio telescope in West Virginia and the SETI Institute's Allen Telescope Array in California were turned towards the object. Fortunately, or unfortunately, depending on how you look at it, no signals were heard.

Yet there are some space-craft going the other way. As relics, the Pioneers and their plaques will keep sailing on towards the stars. Pioneer 10 passed the orbit of Pluto in 1983, before concluding its science mission in 1997, and is now heading roughly towards the red star Aldebaran, which forms the eye of the constellation Taurus (the bull), which it may reach in some 2 million years. Pioneer 11 sent its last signal back to Earth in 1995 and is heading in the direction of the constellation Scutum (the shield), and may encounter nearby stars in a million years or so.

Both Voyagers have already left the formal edge of the solar system, which is defined by the 'heliopause', the outer shell of the bubble of solar wind particles that extend from the Sun. After a few bumps and jostles as they crossed the bubble's edge they are now sailing through interstellar space. It will take at least 400,000 years for them to reach the vicinity of another star. Voyager 1 will glance by a minor one as it heads in the direction of the constellation Camelopardalis (the giraffe); Voyager 2 will pass another in the constellation of Andromeda, before shooting past Sirius, the brightest star in the sky, some 300,000 years from now.

And around these stars, these probes from our solar system may well encounter other planets. Since the 1990s, astronomers have spied thousands of worlds orbiting stars other than our Sun. Challenging to see against the bright glare of their host star, astronomers have come up with crafty ways to detect the presence of these 'exoplanets'.

The star might dim ever so slightly as the planet passes in front of its disk – mirroring the transits of Venus across our Sun. Or the gravitational tug of the planet as it orbits might make the star wobble back and forth enough to affect characteristic frequencies of light or radio waves it emits, giving away the presence of its far smaller companion.

So far, the variety of exoplanets found is spellbinding, and more than enough for any future science-fiction writers to cast away heroes upon. From giant gas planets that would make Jupiter look puny to rocky planets with damp atmospheres, not so different elementally from Earth, it now seems probable that almost every star has some sort of planet around it – harking back to old ideas of multiple worlds. The likelihood of life on any of these worlds beyond Earth remains hard to assess, though many astronomers are trying to weigh the chances and hunt for clues, such as through chemical signatures, although there's as yet no hard and fast test.

As Carl Sagan noted, we don't know whether any of the golden records on our spacecraft emissaries will ever be played. Nonetheless, 'the launching of this bottle into the cosmic ocean says something very hopeful about life on this planet.'

As the names of the Mars rovers reflect, planetary exploration has so far been a hopeful endeavour. We entered the twentieth century believing that there were fellow beings on Mars. We ended that century proving that there was not, at least visible at the surface. But we've gone into the twenty-first hopeful again that we'll find clues in more distant realms, and have even extended our messages to the stars.

3

Destiny

Messages in the Stars

Sky stories

When we speak about the stars we think of the future. We 'reach for the stars' when we struggle towards some far-flung ambitious goal. We 'look to the stars' when we dream. When I think of the stars, I think of a long-awaited trip along the Central Asian Silk Road that I took a few years ago, and of the view of the night sky it afforded me.

As we drove towards Samarkand, the stony desert gave way to an emerald plain, stretching endlessly to the western horizon and interrupted only by occasional pale flecks of farmsteads. It was late March and the trees were just waking, veiled in a spray of fresh green. Our bouncing minibus rumbled on, its creaking chassis dodging potholes and ruptures in the asphalt. We passed bridges that had been washed away during the winter, their carcasses lining chasms eroded by torrents.

The bus slowed and turned onto a farm track that wound up into the hills. We passed clusters of turquoise and white

wooden bungalows set amongst bare-branched fruit trees. When the track narrowed and we could pass no further, we abandoned the bus, taking just enough belongings to pass the night. A fleece jacket, a T-shirt, a toothbrush. We walked up a bramble-edged lane and through farm gates, towards a pair of shiny white domes. Their coats of plastic sheeting flapped and rustled, lashed with ropes against a keen wind.

A smiling couple, flanked by four shy but curious children, beckoned us to make ourselves at home in their yurt. They had just moved up from the valley into their summer home, they told us. They were cleaning up the house, patching broken windows. The facilities were rudimentary – there is no running water up there, only bucketsful drawn from a spring, and the electricity generator is erratic – but they hoped we would enjoy our stay.

After a simple meal of mutton stew eaten under a precariously wired bicycle lamp, and shored up by a little vodka, we headed back towards our shelter. The interior was dark but richly adorned, its trellises webbed with red ribbon and crowned with a chandelier of tassels. The mountain air had an icy edge and it had been a long day. But something distracted us from crawling immediately under the purple, pink and green velvet quilts: the night sky was breathtaking.

The stars were so sharp they might have pierced your retina. And there were so many of them, set amongst fainter swarms, that it was hard to recognise familiar constellations. I could pick out Orion's broad shoulders and belted waist. But was that Cassiopeia's W? I wasn't sure. I spied a bluish cluster of stars – that must be the Pleiades. It struck me that this simpler world was captivating. Away from the yellow glow and bustle of cities the night sky could show off its stark glory. Unleashed, the stars jostled for space and

crowded into our faces. The night sky seemed as low as the roof of our tent.

It was a timeless scene. How many thousands of travellers must have passed this way over the years, on camels and on horseback, in rickety ex-Soviet cars and Chinese-made buses, like ours? Although the landscapes and weather might change, the night sky above is more constant, and regular.

For millennia, the stars have steered travellers in the right direction, across featureless deserts, plains and oceans. Viewed from the surface of our planet, all the stars seem to spin about the north celestial pole. Once you have seen them rise and set many times, and understood how the timing and heights of star motions shift through the year, you can predict where they will be and use them as a heavenly compass.

Bright individual stars and their groupings or constellations have grabbed people's attention. Different cultures have lent their stories to the stars. But our tales, practices and relationships with the stars have much in common around the world.

Australia's early inhabitants can claim to be the first stargazers. For at least 40,000 years on that old and weathered continent they have used the night sky as an encyclopaedia. They have projected onto its dark pages practical advice – on when to travel, hunt or harvest as well as how to behave. Even the faintest stars are portentous. And that knowledge has been passed down through the generations through storytelling and song. To Australian tribes, everything in the Universe is connected. The past, present and future are one, linked through a parallel dimension called 'the Dreaming', where spirits and ancestors roam and trigger change.

Written in this book of the stars are personalities, cautionary tales and life lessons. The rise of the red star Arcturus, the fourth brightest in the sky, tells Indigenous Peoples in Arnhem Land, in the far north of Australia, that it is time to harvest rushes to make baskets. The appearance of the constellation Scorpius, with its coiled scorpion's tail, tells islanders in the north of the wet season's end and the arrival of south-easterly winds.

The orange star Aldebaran warns against committing adultery. It is said to host the ashes of a man who stole another's wife. The flames of the burning tree in which he hid her carried him into the sky.

The Pleiades, a knot of bright blue stars, represents a group of girls and has a special significance for women – a link that's true in many cultures. For example, to the ancient Greeks, the Pleiades were 'seven sisters', pursued by the hunter Orion and his dog, Sirius. In India, the Pleiades are the wives of seven wise men known as the 'seven sages', or the six mothers of the six-faced war god Kartikeya, who developed six heads in order to nurse from them.

Stories about the Pleiades are still given special reverence in Australia today. The deep cultural meaning of these stars was central to a lawsuit about the construction of a bridge in South Australia in the 1990s. Local Aboriginal women claimed that the bridge should not be built because it would desecrate the river and block the passage between the river and the sky of the Pleiades spirit girls, who were linked to creation and procreation. The bridge was eventually built, though a later Royal Commission found in the tribe's favour, albeit too late.

The islanders of Torres Strait, between Australia and New Guinea, have also turned to the stars to defend their practices in the face of modern law. Within the stars are all

their traditional regulations – when to start fishing, sowing and other activities. Yet oral testimony was once inadmissible as evidence in Australian law. In 1992, the Australian government recognised this clash and allowed the islanders to conduct their affairs according to their oral traditions: the stars are now part of the law.

Many other peoples similarly set their agricultural calendars to the cycles of the stars. For example, the Zuni of New Mexico call the Pleiades the ‘seeds’, because they use the constellation to time their planting and harvests. In Inca and Quechua astronomy, the Pleiades are thought of as a storehouse. Throughout South America, the positions of star clusters like the Pleiades and the Hyades and bright constellations like Orion and the Southern Cross are used to signal the onset or end of the dry or rainy season, fishing cycles and even the availability of honey.

Out at sea, where there are no visible landmarks, the stars are vital for wayfinding. The ocean might look much the same in all directions, but the skies give everything away. The Polynesians are some of the most intrepid seafarers. For millennia they have journeyed for thousands of kilometres between remote islands, judging their passage by the positions of the Sun and stars, as well as by subtle changes in the qualities of light, clouds and waves, and the flight paths of birds. One skilled Polynesian navigator called Tupaia guided British captain James Cook in his exploration of the south Pacific, New Zealand and Australia in the eighteenth century, before there were detailed charts of the southern sky.

To a sailor out in the open ocean a bright star lying low on the horizon is a waymark, just as a mountain peak might be on land. And to people travelling in tropical waters near the equator, the stars descend to the horizon through the night

almost vertically, as they circle the poles. Heading for a particular star can offer a clear direction of travel for hours, and checking when a star is at its highest point in the sky can tell you of your latitude.

Sirius, the most intense star in the night sky, burning fiercely white, passes overhead at the latitude of Fiji, and has been central to many Polynesian cultures. In Hawaii it soars to its peak at the winter solstice, when it is celebrated as the Queen of Heaven. Sirius's appearance in the morning sky marks the onset of winter for the Māori. And the coming into view of the constellations Aquila (the eagle) and Lyra (the harp) heralds the end of winter darkness for the Inuit in the Arctic.

Even in an age of electronic wayfinding, knowledge of the stars as a tool for navigation is still a valuable skill. The US navy teaches it to its cadets, for example, in case satellite links are lost. Through the ages, humans have used the stars to navigate the world, physically and societally.

Star charts

Traditional Polynesian sailors have held much of their directional knowledge of the stars in their heads. But they have also systematised that know-how by dividing up the sky into quadrants and defining key lines to follow to particular islands or fishing grounds. They can sketch these out as a series of points marked on a circle, like a set of compass points.

Other civilisations noted the positions of the brightest stars in other ways. For example, as long ago as the twelfth century BCE, Babylonian astronomers measured the directions and heights above the horizon of dozens of key stars during the year. They recorded this information

systematically on their clay tablets and used these stars as reference points for tracing the planets that wandered amongst them, noting nightly relationships in a succession of hundreds of tablets known as the Astronomical Diaries. They defined groupings or constellations of stars, with names that meant something to them, such as the bull, fish or lion.

By the second century CE, in ancient Greece, the mathematician and astronomer Ptolemy published tables of the locations of the 1000 brightest stars, as well as those of the five then-known planets.

But long tables of numbers are dry to even the most enthusiastic observer, and they are hard to relate to the real sky. Pictorial charts are much more appealing. They are better too at conveying the stories behind the familiar stars that speak of our destinies. For example, what Westerners would recognise as the belt and torso of the mythical hunter Orion are recognisable in the earliest known paper chart of the stars, which was found in 1907 in a cave on the edge of the Gobi Desert, near Dunhuang in northwestern China. The cave, carved into cliffs, is one of hundreds of early Buddhist temples, known as the 'Caves of the Thousand Buddhas'. Their rooms are crowded with statues and murals.

The Dunhuang chart was sealed in the caves along with thousands of other manuscripts around 1000 CE and, fortunately, survived intact in the arid conditions. The temples were rediscovered, accidentally, in the early 1900s. British-Hungarian archaeologist Aurel Stein visited them within a few years of their opening and brought the atlas and other items back to the British Museum in London, where it still resides. Most of the documents in the caves were Buddhist religious texts but a few were scientific. The impressive star atlas, and another fragment showing stars

near the north pole, was found amongst calendars, almanacs and medical treatises.

The Dunhuang star atlas probably dates from the seventh century CE. On a four-metre-long scroll made from mulberry fibres, it depicts stars in the whole of the northern sky as seen from the line of latitude that cuts through Tibet and mid China.

The Dunhuang star atlas hums with energy. Strings, zigzags, fans and arcs of black and red dots dance across the page. Each shape is labelled and groups of them are fenced in by long strings of Chinese text. A menacing bowman wearing a head-dress and tunic, perhaps the god of lightning, stands at one end. Is he leading the procession or warning you to back away? Either way, he seems to control the power of this starry menagerie.

The night sky, in Chinese tradition, was not just the domain of gods and supernatural beings. It was a mirror of the human world as well. In texts dating back to the fifth century BCE, the heavens were partitioned into areas representing regions of China's empire. Celestial omens were read like a futuristic news bulletin, a forecast of events on Earth. And the job of identifying and interpreting omens was very much a government role, essential for ruling the state.

Chinese dynasties kept banks of astronomers at work, much like civil servants. Failing to predict an eclipse could be a death sentence, but centuries of meticulous recording of the heavens put Chinese astronomy ahead of the curve. Comets, sunspots and supernovae were first seen and documented by Chinese astronomers, and their historic records are still relevant today. For example, in 1054 CE Chinese astronomers logged the bright explosion, or supernova, of the dying star that formed and now sits at the

heart of a dramatic bubble of glowing gas called the Crab Nebula.

Each culture writes its own stories into the sky as constellations. A star is a letter that can be strung into words and sentences. In Western eyes the major groupings are generally large and few in number, many associated with ancient figures from Roman and Greek myths, from Orion the hunter to vain queen Cassiopeia and helpless heroine Andromeda. Later patterns were named after preoccupations of the times.

When southern skies demanded new constellations, European explorers named them after parts of their great ships (Argo Navis), from the keel (Carina) to the poopdeck (Puppis) and sails (Vela). In the eighteenth century, fashions for science and navigation provoked Circinus (the compass), Octans (the octant) and Microscopium (the microscope).

By contrast, Chinese constellations, such as those that crowd the Dunhuang scroll, are smaller and number in the hundreds. Most groupings have symbolic meanings, like the signs of the zodiac. Many relate to particular objects and people, heightening their astrological powers of prediction, some of whom are represented by just a single star. It's hard to misjudge an omen when pinned to a celestial landmark so tightly. And the landscape of the night sky was mapped out precisely.

The Chinese sky is divided around the equator into five 'palaces', four linked to a cardinal point and a season, plus a ring around the north pole. The 'blue dragon of the east' is associated with spring. The 'fire star', the bright red star we know as Antares, is the dragon's heart. The 'red bird of the south' heralds summer and the 'white tiger of the west' calls upon autumn. The 'black tortoise of the north' represents winter.

The circumpolar stars, which never set, were most important in ancient China. The pole star symbolised the Emperor himself, the person around whom everything revolved. Positions to the north conferred greatest status, and this was where the queen, princes and ministers also resided. Surrounding constellations represented court dignitaries, bureaucrats and parts of Beijing's imperial palace. The band through which the planets wandered had its landmarks such as the celestial gate, street and fortress.

Scenes from everyday life were also played out in the stars. Common people and army troops sat to the south, where they sometimes fell below the horizon. The autumn sky contained a sign for the harvest. There was a celestial marketplace, containing a variety of shops. Forms of transport were noted, and various buildings: there is even a toilet.

As well as human society being mirrored in the stars, ancient Chinese civilisations built structures on the ground to reflect celestial alignments. In the second millennium BCE, when the first large, planned cities were constructed, palaces, city walls and tombs were aligned to the cardinal directions. In 221 BCE, after he overcame the 'warring states', the First Emperor of Qin used cosmic alignments to cement his universal power at his new capital of Xianyang (today in Shaanxi province in north-central China). He associated the main palace with the north pole and built a network of secret walkways linking many palaces on either side of the Wei River (a tributary of the Yellow River), which symbolised the 'River of Heaven' or Milky Way. Key buildings in Beijing's Forbidden City are similarly aligned on its north-south axis.

Weaving and silk-making metaphors, such as cord, warp and weft, were widely used in ancient China, too, when

discussing interlinkages between humans and the cosmos. For example, the striking hook-shaped northern constellation that we know as Ursa Major, or the Great Bear, Dipper or Plough, was said in ancient China to resemble a 'top cord', the loose knot used in looms to gather all the warp threads together. Such symbols spoke of social and celestial orderliness, woven by governance into a single fine fabric.

Astronomical instruments

While the stories people have written into the heavens vary, the tools used to measure the stars are much the same around the world. One of the simplest is the sundial. A stick placed in the ground yields much information as its shadow rotates through the day, shortening as the Sun rises in the sky and lengthening again towards dusk. A star's height or angle above the horizon can be read off by sighting it against a scale, like a protractor, marked in degrees. This is the basis of quadrants and sextants, which are named after the fraction of a full circle that each covers: a quadrant spans a quarter (ninety degrees), and a sextant a sixth (sixty degrees), of a circle.

Civilisations went to so much effort to map the sky because the messages in the stars *mattered*. Astrology guided the actions of emperors as much as charts aided travellers. Astronomical knowledge and tools were traded. Along the Silk Roads, Chinese, Greek, Roman and Islamic know-how intermingled. Samarkand, in modern-day Uzbekistan, was one important hub. And I was more than excited to visit its historic fifteenth century observatory on my visit to the region.

Just to the north of central Samarkand, perched on a small unremarkable hill surrounded by dusty freeways, lie the ruins of the observatory. It belonged to a great leader and scholar called Ulugh Beg. He was the grandson of a famous fourteenth-century warrior – Timur, also known as Tamerlane, who waged campaigns across Central Asia, as far afield as Delhi, Kabul and the shores of the Caspian Sea. Like his grandfather, Beg was a fierce intellectual as well as a fighter. He set up madrassas in Samarkand and Bukhara to teach Islam, science and the arts. He was progressive and, for example, supported educating women.

Beg's observatory was the finest and largest in the world at the time. Not much of it remains today, but what does is striking – a vast pair of curved double rails that was once part of a huge sextant. Protected from the elements by a flared metal roof, like a trumpet bell on its side, the rails plummet down into a deep trench and up again, like part of an ancient rollercoaster. Their smooth surfaces of white marble glint like metal.

An arc of a circle forty metres in diameter, the sextant would have filled much of the three-storey round tower that once formed the observatory. The lower rails were cut into the hill's raw stone and the higher edges were propped up by brick walls. Arabic symbols and lines etched into the rails mark off degrees and smaller gradations. Astronomers would have read off the angles of faint shafts of starlight entering the dark observatory through a hole in the roof. The great size of the sextant delivers its precision, of one six-hundredth of a degree, a level of accuracy that was not bettered for two centuries and is still respectable today.

Beg's approach to science was methodical and, to us, very modern. He employed more than sixty astronomers and mathematicians to take measurements, at least two of

whom had to be present for each observation. He demanded that all results be discussed by a group and encouraged debate and dissent. He even posed false questions to flush out those who simply wanted to please him. Beg didn't want to be told what he wanted to hear: he wanted to know, really, how is the Universe turning? Such careful habits of double-checking and questioning data are sometimes bypassed in the fast-paced world of research today.

A small but fascinating museum opposite the sextant houses reproductions of other astronomical instruments that were once used at the Samarkand observatory. They include armillary spheres – globe-like models representing the passages of the Sun and Moon and other celestial objects as interlocking hoops. There are similarities to others found along the Silk Road, from Persia to China to Europe. Glass cabinets protect scores of old Arabic books, mostly later copies of Beg's works, that lie open to reveal scientific sketches and lists of measurements. Scale models of the observatory are sliced away to reveal its contents and rooms, offset from the sextant's curved skeletal spine.

Notable amongst Beg's many achievements is his catalogue of over 1000 of the brightest stars. Known as the *Zij*, it was far more accurate than Ptolemy's *Almagest* and was widely translated into Arabic and Persian. Beg is widely regarded as being the greatest astronomer since Ptolemy and before the rise of Western science.

Beg's influence spread first across the Islamic world. In Constantinople (now Istanbul), royal astronomer Taqi ad-Din persuaded the incoming Sultan of the Ottoman Empire to build a great observatory to rival Beg's. Completed in 1577, it contained similarly fine instruments. But it was destroyed just a few years later when, as we have seen, the

astronomer's interpretation of a comet's appearance failed to deliver the desired prediction to the Sultan. Later, in eighteenth-century India, Maharajah Jai Singh built vast masonry instruments much like Beg's at five sites including Delhi and Jaipur.

In the west, Beg's pioneering work remained obscure for long enough that other astronomers were able to catch up. While translations of Islamic and ancient Greek scientific texts fed into European scholarship through the 'dark ages', it was not until 1650 that the *Zij* was published in Latin in London. It took another fifteen years for the first European editions of his star tables to be printed.

In the meantime, just as Constantinople's observatory was being torn down, aristocratic Danish astronomer Tycho Brahe was completing his world-class observatory at Uraniborg in Sweden. The quality of Brahe's array of sextants and quadrants enabled him to exceed Beg's feat and in 1580 Brahe published a catalogue of the 1000 brightest stars with even greater accuracy. It would take telescopes, trade and adventure to do more.

Over the next few centuries, surveys of the sky got better. The arrival of telescopes in the early seventeenth century enabled astronomers to see thousands of fainter stars. The maritime expansion of Europe into the 'new world' exposed the southern skies to scrutiny. But something was still missing. Charts and tables locate the stars in two dimensions, vertically and horizontally. But they tell you nothing about the third, distance. Attempts to measure distances to the stars began to map out our celestial surroundings, and our place in the Universe.

Our cosmic backyard

In the nineteenth century, astronomers started to work out how far away the stars are. They borrowed the techniques of terrestrial map-makers and used the concept of triangulation, or parallax, to measure distances. Just as you perceive an object to shift slightly left and right when you close one eye and then the other, the position of a star changes slightly when viewed from Earth depending on where the planet is on its orbit around the Sun. The nearer the star, the greater the shift appears, and by taking measurements from Earth at two different times of the year it was possible to calculate the differences.

The first lesson from making these measurements was that stars are really far away. The shifts are so tiny that it took centuries for instruments to improve enough to be able to detect them. In 1838 German astronomer Friedrich Bessel managed to see the shift of what turned out to be the nearest star to Earth. Proxima Centauri wobbled by less than one second of arc every six months. That is ten times finer than a grain of sand seen from ten metres away, and hundreds of times smaller than Beg's or Brahe's sextants could manage.

The resultant numbers are staggering. We now know that Proxima Centauri is 39,900,000,000,000 kilometres away, or 271,000 times the distance of Earth to the Sun. Even light, which travels three million kilometres in a second, takes more than four years to reach us from Proxima Centauri. More distant stars have even longer light passages and tinier parallax shifts.

Parallax is also difficult to measure for the same reason that mariners struggle to reach a destination by simply following a bearing read off a map. Currents and winds may blow them off that direct course, so a sailor crossing a fast-moving river or windy stretch of sea knows to aim slightly

upstream or upwind. Likewise, astronomers need to correct for the motion of the Earth through space.

While the first measurements of distances to the stars were made painstakingly, one by one, the advent of photography made it possible to make many such observations at once. Long exposures could also collect the light from stars much fainter than the eye can see.

The first photograph of a star, Vega, appeared in 1850. Within a few decades the whole sky was surveyed. The Paris-led Carte du Ciel project marshalled twenty observatories and an army of staff or 'computers' around the world to record the positions of millions of stars. By 1910, more than 360 of those stars had distances measured, found by looking for stars whose positions shifted back and forth between photographs taken half a year apart.

From the 1970s, photographic plates and film were replaced by electronic cameras and digitised maps of the sky, but even in the 1990s, copies of the old plates were still widely used in universities and observatories. As a graduate student, I recall sitting down one afternoon, clutching a cup of tea in a library side-room, to scan photographic films of patches of the night sky. A foot wide, each negative plate was spattered with tiny grey dots and smudges. Each mark had a story to tell. Here a dying star; there a cradle of newborn ones. Here a dwarf galaxy; there a massive one with a central black hole. All looking like crumbs of cake thrown across the table. My job was to find out what some of these dots were. It was engrossing.

But for measuring really accurate stellar positions, even the best eyes, telescopes and cameras on Earth can only do so much. Turbulent air makes stars seem to flicker: to minimise that, astronomers have had to put their telescopes

into space. In 2013 the European Space Agency launched its Gaia mission to chart the positions of two billion stars and find the distances to millions, reaching tens of thousands of light-years from Earth. Diligent projects like this are starting to map out our cosmic back yard accurately.

If the solar system is our immediate family, forty stars lying within a dozen light years of us are our cousins. Only nine of these stars can be seen with the naked eye. Our closest neighbours of all, at just over four light years away, are a triplet of stars called Alpha Centauri A, B and C.

This trio lies in the southern sky. Stars A and B are twin suns, orbiting one another every eighty days. For years they were thought to be a single star, equivalent to the third brightest in the sky: only with high enough magnification can they be seen to be two separate stars. This source is also one of the Pointers, two bright stars that direct the eye to the Southern Cross.

Alpha Centauri C is the closest of the three to us, and often goes by its other name, Proxima Centauri. It is a faint 'red dwarf', a glowing ember of a burned-out star. But it is close to us in another way. In 2016, a planet a little larger than Earth was found orbiting Proxima Centauri every eleven days.

The surface of this 'pale red dot' should be warm enough for liquid water to exist, raising the potential that it could host oceans. But there is little hope of ever finding life there. The shrivelled star wields a powerful magnetic field that draws in passing gases. As the gas burns, the star flares and scorches the planet's surface with deadly X-rays. Should we ever be able to travel to this place, we would need shields made of lead to protect ourselves from the radiation.

The best known of the stars visible to the naked eye, though, is Sirius, the brightest star in the heavens, which

lies nine light years away from us, twice as far as the Alpha Centauri group. As the luminous pinnacle of our heavens, Sirius has evoked many cultural meanings. Ancient Egyptians linked Sirius's rising with the flooding of the Nile, a guarantee of the land's fertility. Its Latin name comes from the ancient Greek word 'seirios', which means glowing or scorching. It is also known as the Dog Star, because it sits in the constellation of Canis Major, the great dog. In China, Sirius is known as the 'celestial wolf'. The ancient Greeks associated the rising of Sirius with the 'dog days of summer', when the heat becomes unbearable. The Greeks supposed its emanations were bad, and described those afflicted as 'star-struck'.

Sirius can also appear to twinkle ferociously in hazy weather. Its hues can flicker too, like fire in a diamond. These are not its true colours but tricks played by Earth's atmosphere, which distorts red, green and blue wavelengths of light differently, causing these iridescent flashes.

Some stars do have dominant colours, though, which betray their temperature. Just as for a hot coal or a steel poker, a red star like Arcturus is cooler than a white star like Sirius. A blue star like Rigel is hotter still. The colours of stars evolve as their cores burn. An average star like the Sun starts out blueish-white and will fade to rusty brown over billions of years. Eventually it will cool and bloat until its inner fires choke off. Its core will collapse back into a cold, dense husk called a white dwarf.

Sirius, indeed, shows both these traits. It too is a pair of stars orbiting one another, too close to separate by eye; a brighter, fatter cousin of the Sun entangled with a pale white dwarf. Although these stars look very different today, they were more similar hundreds of millions of years ago. But that small variation led each to a different fate. The

second star was slightly larger than the first and consumed its fuel faster, dying younger than its sibling.

Stars larger than the Sun burn even hotter and exhaust themselves more quickly, within hundreds of thousands of years. When a star burns, the resultant heat creates pressure, causing it to expand, but this expansion is held in check by the inward pull of gravity. When the central furnace switches off, without that heat pressure, gravity pulls material into a denser ball. The outer gas layers crash back onto it so fiercely that the whole star shudders and explodes as a supernova. All that is left afterwards is the dense core, known as a neutron star, sitting inside a rarified bubble it has blown out within the surrounding gas.

Astronomers now believe that the Sun and its nearby stars lie in such a supernova bubble, a vast cavity 300 light years across, evacuated by the death of a past star. The bubble is shaped like an hourglass, its waist cinched by dense gas clouds that blocked the blast. Our local bubble links to other cavities made when other stars erupted. As well as lying close to a family of other stars, we are living in a sponge-like warren tunnelled out of clouds of hydrogen.

Our cosmic neighbourhood would have confounded ancient astronomers in another way, too. The nearest stars are not 'fixed' on the sky, as the ancient Greeks thought. Just as the Sun is travelling through the Milky Way, all stars are nomads moving through space. For most stars, this motion is too slow for us to witness, which is why the sky seems unchanging. But over thousands or millions of years, once-familiar aspects of the night sky alter. Sirius, for example, has moved half a degree across the sky since Ptolemy noted it in his *Almagest*. In the 1830s, astronomers realised that the Alpha Centauri trio is rushing towards the Earth.

In tens of thousands of years, the Pointers will no longer be a useful celestial signpost; the stars within constellations are not, after all, connected with each other in any way other than how they look from Earth. Alpha Centauri will pass north of the Southern Cross before heading northwest, away from the band of the Milky Way. It will slowly brighten as it approaches us, passing to within three light years of Earth. Then its stars will gradually recede and dim. Just as Ulugh Beg's observatory now lies as rubble in the midst of a modern city, 100,000 years hence these stars will be indistinct specks, lost amongst the glitter of the Milky Way.

Anchoring the whole colourful cast of constellations, the Milky Way's faint stream of light stretches roughly east-west across the sky. It was known in Latin as the 'via lactea' and in Greek as the 'galaxías kýklos' or 'milky circle'. (The word galaxy also stems from 'galaxías'.) Although more imprecisely defined than a constellation of stars, the pale band has still played a huge role as a celestial 'skymark' in many cultures. And unravelling its secrets has led to jaw-dropping discoveries – including that we live in a bounded swarm of stars, or galaxy, that is just one of many.

Milky Way

What is the Milky Way? Ancient Greek philosophers wondered about this many centuries ago. Aristotle argued it must be a haze of fiery gases; Anaxagoras, Democritus and some Islamic scholars believed – rightly as it turned out – that it was a concentration of stars. Italian astronomer Galileo Galilei confirmed this in 1610 when he looked at the Milky Way through his telescope and saw the band break up into many individual stars. We now know that it contains hundreds of billions of stars, including our

Sun, as well as clouds of gas and soot that appear as dark blotches along the pale band.

Why does it appear as a band on the sky? The stars within the Milky Way are arranged in a flattened thin disk with an oval bulge in the middle, a little like two back-to-back fried eggs. When we look at the Milky Way, we are looking through the plane of stars in the disk. The Sun also sits towards the edge of the Milky Way, so we see more stars towards one part of the sky. That centre happens to be in the southern hemisphere, in the constellation of Sagittarius, and it is from those latitudes that the view of our stellar girdle is most dramatic. It is also where the Milky Way has had its greatest cultural impact.

To Indigenous Australians, for example, the Milky Way is the arc of a great river spanning the sky. The bright stars are fish and the smaller stars are water lily bulbs. Quechua speakers of the Peruvian Andes describe the Milky Way as a river that divides in two, both channels crashing together in a spurt of foam near the constellation of the Southern Cross.

Other groups variously see the Milky Way as a snake, a stream of semen in a cosmic embodiment of fertilisation, or a pale road along which humans, animals and spirits move. Indigenous peoples in Guiana refer to the Milky Way as the 'path of the tapir' or the 'path of white clay'. Ava Guaraní people in Bolivia speak of it as the 'path of the rhea', whose head lies in the constellation of the Southern Cross. In Brazil, the Trumai see the Milky Way as a road to the afterworld; the Tapirapé see the 'path of the shaman', along which human spiritual guides travel to visit celestial bodies.

To watchers of the southern sky, the dark clouds within the Milky Way are just as important heavenly markers as bright groupings of stars. Many of these clouds are identified with animals. Among the Quechua, these include

a snake, a toad, a mother llama with her baby, and a fox that pursues the llamas. Dwellers in tropical forests associate the clouds with jaguars chasing anteaters and deer along the Milky Way path. The Campa in central Peru view the prominent dark cloud lying near the Southern Cross, known in the West as the Coalsack, as a bees' nest; the Múra in Amazonia see it as a manatee. The rising and setting of these ashen celestial features are also linked to natural cycles, such as hunting seasons.

In China, the Milky Way is known as the Silver River, after an ancient myth. In it, the Queen of Heaven draws a line in the sky with a silver pin to separate two lovers – the weaver girl Zhi Nu, associated with the bright star Vega on one side of the line, and cowherd Niu Lang, linked to another luminous star Aquila on the other. The legend, described in poems and still performed in Chinese opera, dates back at least two thousand years.

Zhi Nu, the story goes, was the youngest of seven daughters of the Queen of Heaven, and a weaver of fine clouds. One day, she and her sisters escaped the palace to bathe in a stream. When they came out, she found her fine silk clothes missing, preventing her from flying back into the sky.

Niu Lang popped up clutching her silk dress. He was an orphan, driven out of his home by a cruel brother and his wife to live with his only friend, his cow. Niu Lang longed for a companion and pleaded with Zhi Nu to stay with him, which she did. The two married and lived happily together – until the Queen discovered Zhi Nu was missing and whisked her back to heaven.

Watching his wife fly into the sky, Niu Lang was terrified. He reached for the hide on the wall that his faithful cow had left him. It lifted him into the sky in pursuit of Zhi Nu. He had

almost reached her when the Queen appeared and drew a magical line of silver between the two. This became the Silver River of the Milky Way, dividing the two star-struck lovers on either side.

Eventually, so the legend goes, the Queen took pity and permitted them to meet once a year on the Milky Way, on the seventh night of the seventh month in the Chinese lunar calendar. This meeting is still celebrated in China in the 'seventh night' or Qixi festival. Much like on Valentine's Day, newlywed couples look to the celestial pair for marital happiness. Girls ask Zhi Nu to endow them with good needlecraft skills and to find them a good husband.

In Japan, the equivalent deities are called Orihime (Vega) and Hikoboshi (Altair), and the occasion is known as the 'star festival'. It is also known as Tanabata, after a loom used in a traditional Shinto ceremony, which became merged with this star celebration, in which a young Shinto priestess wove a special cloth for the gods to pray for a good harvest.

My own love of the Milky Way flourished when, in the 1990s, I worked as a graduate student at the University of Sydney in Australia and I would regularly visit the Anglo-Australian Telescope in rural New South Wales to study the light from distant galaxies. As we worked through the night, whenever I got a chance, I would go and stand outside the dome, up high on a steel mesh balcony, to take in the magnificence of the night sky away from the city.

The austral sky isn't a black void with a few hundred stars strewn across it, like diamonds on black velvet, as much of the northern sky is. It is a carpet of colour, a tapestry of lights spreading as far as you can see in all directions. As your eyes adjust, you see more and more stars, swimming in foaming baths of glowing dust, and the dark gas clouds,

like the Coalsack, sitting like shadowy pools in the Milky Way stream. The two Magellanic Clouds, large and small, lie towards the horizon. The size of a thumbprint on the sky, each appears like a distant metropolis harbouring billions of suns.

It's certainly immense, but figuring out the exact size of the Milky Way has not been straightforward. Today, painstaking space missions, like ESA's Gaia, are beginning to map and pin down distances to hundreds of millions of stars using the method of parallax, or triangulation. But, even so, there are so many stars in the Milky Way that they cannot locate them all. Astronomers still only have a loose idea about its detailed structure. And until quite recently, pretty much all they had to go on were two-dimensional views of the sky, with no way to tell the difference between a bright star lying far away and a dull one nearby.

Plus, there are far more objects than just stars in the night sky. Stars look like points of light or sharp dots on the sky. But between them, if you look carefully through a telescope, there is also a dusting of fuzzy objects. Some of them look like smeary blobs or paint spatters. Some are oval and elongated. And some are swirls, or tiny spirals, looking much like Catherine wheels or stirrings of cream on top of a cup of coffee. What were these fuzzy whorls? Early astronomers had no idea. But they did have lots of theories.

Spiral nebulae

Ever since Galileo had showed that the Milky Way is made up of many stars, debates around its shape and size had raged. The idea that the stars inhabited a disk gained traction. In 1750, English astronomer Thomas Wright suggested that the Milky Way might be a grander version

of the solar system, where all the stars, including the Sun, were held in orbits within a plane. While that made a lot of sense, Wright speculated further that the faint smudges seen amongst the stars were not part of the Milky Way system but 'external creations, bordering upon the known one, too remote for even our telescopes to reach'. However, he had no proof for this bold idea.

Intrigued by these arguments, in 1755 German philosopher Immanuel Kant followed up on Wright's work with a treatise of his own, called *Universal Natural History and Theory of the Heavens*. The treatise remained unread for around fifty years, as the copies, which Kant had authored anonymously, were impounded after his publisher went bankrupt. Yet, eventually, his work did prove influential.

Kant agreed with Wright that the bright band of the Milky Way must be a disk of stars, behaving much as the planets in the solar system do when orbiting the Sun. But he also went further. The stars must move like planets, he reasoned, because they follow similar laws of motion – namely those obeying the force of gravity, which Isaac Newton had set out in *Principia* in 1687.

If gravity is acting upon the stars, Kant posited, then it's likely, too, that the force must also have drawn together the matter that stars and planets are made from. And that must mean that, much earlier, this matter must have been spread more diffusely, as a mist of atoms filling space. Forces of attraction then led to heavier elements accruing lighter ones. And repulsive forces might have played a role too, Kant thought. When particles came too close, he suspected, they would repel one another, spraying out like a puff of perfume. All this pushing and pulling swept up particles into

vast whirlpools, he surmised, which settled into circular disks within which heavenly bodies formed.

It was quite a vision, and the implications were huge, too. That such 'blind mechanics' could explain the orbits of planets in the solar system, and probably the stars, and perhaps everything in the whole Universe, was remarkable. It left no need for a 'divine creator', Kant pointed out, admittedly apart from perhaps setting up the laws of nature at the start.

Kant's bold idea was more conceptual than scientific – beyond gravity, it didn't account for other physical laws like the conservation of energy or the physics of rotation, for instance. And the scale of the Milky Way and even distances to the stars were still unknown. But with nothing more to go on, Kant went along with Wright's presumption that some of the fuzzy nebulae in the sky might well be separate clumps of matter beyond our Milky Way. He referred to them as 'island universes'.

In 1785, trying to measure the shape of the Milky Way more precisely, British astronomer William Herschel attempted to count the numbers of stars in different parts of the sky. He published a map, showing a broad oval swathe of stars. These stars were fairly evenly spaced, he noted, which he took to imply that the Sun was in the centre of the stellar swarm. But, just as astronomers before Copernicus had been convinced that Earth lay at the centre of the cosmos, Herschel's assumption was incorrect. He hadn't taken into account that clouds of dust obscure stars on the far side. He was essentially only measuring the density of stars near to us.

That realisation led to more debates. How many stars might be hidden from our sight by dust clouds? In 1823, German astronomer Heinrich Wilhelm Olbers proposed that

such obscuration might even explain the darkness of the night sky – a long-standing philosophical puzzle. But Olbers' suggestion tumbled quickly. If it was true, the energy from the absorbed light would heat up the intervening material, making the sky glow brightly at infrared wavelengths. And it doesn't. Nonetheless, the question of why the night sky is dark has been known as Olbers' Paradox since.

Why is this a paradox? Because if stars in the Universe go on forever, then there should be one at the end of your sightline everywhere. Imagine being in a vast forest of trees. Everywhere you look you see tree trunks. You cannot see out of the woodland to the landscape beyond. Similarly, the sky would appear bright in all directions; there would be no night. Clearly that's not the case.

So, why might it be dark? Johannes Kepler proposed back in 1610 that there was a limit to the number of stars in the Universe. They did not fill the sky. And that's what astronomers know to be true today. But the reasons why our *view* of them is limited is far more complex and profound, and would take centuries to unravel.

A third explanation for why the night sky is dark came, curiously, in a lengthy 1848 prose poem by American writer Edgar Allan Poe. In 'Eureka', Poe set out his ideas on the nature of the Universe, which he had also shared in a lecture in New York. Few people attended that talk, and literary critics failed to see the relevance of his latest work, decrying it as something that could have been written by a schoolboy or as the rantings of a madman. Poe stood firmly by it, though, claiming it was the most significant work of his life, and writing in its preface that it should be judged only after his death.

Poe tasked himself with describing the character of the whole Universe: 'the utmost conceivable expanse of space,

with all things, spiritual and material, that can be imagined to exist within the compass of that expanse'. He tried to deduce its life story – and eventual death – as if through a plot in one of his detective novels. And he succeeded persuasively, to an extent that is still surprising almost two centuries later.

As a first step, Poe deployed humour to take down philosophers and scientists of old for not thinking out of the box. Among them were Aries Tottle (for Aristotle) and Hog (perhaps Francis Bacon, father of the scientific method). He lambasted scientists for hiding behind the veil of facts and theory and for limiting their inquiries. It was better to admit one knew nothing, he wrote.

Take 'infinity'. The idea of something boundless is just that, an idea, he explained. It's obviously an impossibility, utter nonsense. Instead, Poe preferred to refer to the 'utmost conceivable expanse' of space, as it appears in our imagination. He cited French mathematician and physicist Blaise Pascal's description of the Universe as a sphere 'of which the centre is everywhere, the circumference, nowhere'.

While Poe had no idea how far away the stars and nebulae were, he did recognise that we see them as they were long ago, when the light left them. They are the 'phantoms of processes completed long in the past'. He recognised too that telescopes allow us to see that the Universe is a 'cluster of clusters'. The Milky Way is one such cluster of stars.

Outlining Olbers' Paradox, Poe supposed that the distance to anything in the dark recesses of the Universe – 'yawning chasms, blacker than Erebus' – must be immense, so that 'no ray from it has yet been able to reach us at all'. If there

is anything beyond our visible Universe, then it must not be part of ours, Poe reasoned; it must have no effect on us.

The author concluded his imaginative work by asking what fate might befall the Universe. Attraction must win out in the end, he felt. All the stars would eventually come together in a cataclysmic 'common embrace', when everything – material and spiritual – will become one.

'Eureka' is quite a ride. It's an intriguing encapsulation of ideas whirling around at the time. But was it robust? Surprisingly much of it still resonates with scientific knowledge today – or, put another way, we hold on to these ideas tightly. But, as ever, there's much more to it, as twentieth-century astronomers would find out.

The great debate

Over the next hundred years, astronomers continued to struggle with nailing down the scale of the Milky Way, until US astronomer Harlow Shapley, working at Mount Wilson Observatory near Los Angeles in California, took a completely different approach. Shapley was fascinated by 'globular clusters' – spherical conglomerations of many stars, held together by gravity and packed so densely towards their centres that each looks like a burst of fireworks.

The astronomer mapped out where the globular clusters lay on the sky, finding that they weren't spread evenly, with more sitting in one half of the sky. Thus, he concluded, we are not sitting at the heart of their distribution. He then applied the latest astronomical techniques to measure their motions and distances to them.

Shapley was able to tell how the star clusters were moving relative to us. Light waves emitted from a star

moving towards us are slightly compressed, so the light seems a little bluer – or ‘blueshifted’. Light emitted from a star moving away from us gets stretched and appears a little redder – or ‘redshifted’. You can hear a similar effect with sound waves when an ambulance passes you – the siren noise screeches from high to low pitches as it moves by. This phenomenon is called the ‘Doppler shift’ (after physicist Christian Doppler, who described it in 1842). Another method for this, which had recently been discovered, was based on the properties of a special type of star whose brightness varies in a predictable way. They are known as Cepheid variable stars, after the first one to be discovered (by English amateur astronomer John Goodricke in 1784), called Delta Cephei, in the constellation Cepheus.

In 1912, Harvard astronomer Henrietta Swan Leavitt, one of a group of prominent female astronomers at Harvard College Observatory who between them made many breakthroughs around the natures of stars, established that the more luminous the Cepheid star, the longer it takes to brighten and dim. This relationship between brightness and variability can be used to infer the star’s distance. Measuring the time it takes for the star to flare and fade tells you how bright it is intrinsically. Then you can work out how far away it is by how relatively faint it appears, such that distant stars appear dimmer. Astronomers refer to heavenly bodies like Cepheids where their intrinsic brightness can be established as ‘standard candles’ – much like standard lightbulbs have fixed wattages.

In 1919, Shapley put everything together. To explain their distribution, the globular clusters must lie mostly within a sphere that was centred not on the Sun but on a distant point towards the constellation Sagittarius. That point was at least 30,000 light years away. He also proved that the

Milky Way is really big – at least 300,000 light years across, or ten times bigger than had been supposed before.

That the Milky Way was so vast convinced Shapley that the spiral nebulae sitting amongst the stars must also be part of it. Otherwise, the distances at which they must lie would have to be even more enormous – millions of light years away at least.

But not everyone agreed. Another prominent astronomer, working just up the road, came to the opposite conclusion based on a different set of observations. Heber Curtis, at Lick Observatory near San Jose in California, favoured Wright's and Kant's view that the spiral nebulae were separate 'island universes'. Take the largest spiral, found in the constellation Andromeda. As well as hosting more novae (flashes from dying stars) than were typical in the rest of the sky, the Andromeda nebula's redshift was too large for it to be bound by gravity to the Milky Way. It was moving so fast it should fly off.

Curtis also saw dark streaks in many of the nebulae, which he thought were analogous to the dust clouds in our own galactic skies. As the spiral nebulae looked so much like our Milky Way, it made sense that they might be distant cousins.

Who was right? Science progresses by throwing up ideas and then disproving the bad ones. And some of the greatest breakthroughs come from academic spats, which can be ferocious when reputations are at stake. The scale of the Milky Way was a worthy subject for heated debate. And on 26 April 1920, Shapley and Curtis rolled up their sleeves to do rhetorical battle at the Smithsonian Museum of Natural History in Washington DC.

With each man given forty minutes, the pair put their cases. Shapley, the young and ambitious but nervous

contender, went first. He read unemotionally from a typewritten sheet of notes. The more established, bald and bespectacled Curtis went next. A 'small, quiet man with a remarkable sneeze', as one colleague put it, Curtis was a sharp-minded and forceful orator who had worked as a schoolteacher before furthering his studies. An experienced lecturer, he used slides to ram home his points and to leave the stronger impression on the audience, who were a mix of scholars and members of the public.

To back his case that the nebulae were at similar distances to the stars, Shapley pointed to the size of the Andromeda nebula, the largest of the spirals. It must be close, he said, since it would have to be unfeasibly enormous if it was far away. Also, a nova had been spotted in the Andromeda nebula that was so bright it outshone all the others: this would be insanely luminous, he argued, if it lay at a vast distance.

Curtis then contended that the spiral nebulae were different from other gas clouds within the Milky Way. He presented his evidence that there were more novae in the Andromeda nebula than in other regions around it. Why should it look so distinctive if it was just another nearby gas cloud?

The minds of those listening must have boggled. But there was no immediate conclusion. That would have to wait for several more years. Meanwhile, both claimed to have 'won'. But in hindsight both fell short too, with Shapley's Milky Way too bloated and Curtis's too small and centred too near the Sun.

In 1923, the case was settled by another American astronomer, Edwin Hubble. He used the world's then-largest telescope – the 100-inch diameter Hooker telescope at Mount Wilson Observatory – to distinguish individual stars in

the Andromeda nebula. In October, he found a Cepheid variable star within it. This was crucial as it told him how far away the spiral was – some 700,000 light years away, and well beyond the Milky Way's outskirts, as he went on to report. (We now know it is more like 2.5 million light years.) Hubble underscored the result by using Cepheid variable stars to pin down distances to some other spiral nebulae, showing they lay even farther away.

In the end, Curtis was proved right, and he accepted the answer calmly: 'I have always held this view, and the recent results by Hubble on variables in spirals seems to make the theory doubly certain.' Shapley found it harder to concede, as his Harvard colleague Cecilia H. Payne-Gaposchkin later recalled, having been in his office at the time. 'Here is the letter that destroyed my Universe,' he reportedly said as he held out a piece of paper sent from Hubble.

Outside academia, the reception of this enormous scientific breakthrough was more muted. It took Hubble another couple of years to take more observations and to write up his results in the *Astrophysical Journal*. When he did, the *New York Times* was only moderately interested. With the scale of the Milky Way and recognition of galaxies beyond our own apparently holding far less appeal than torrid accounts of life on Mars, on 22 Jan 1926, the editors plumped for a short briefing.

The headline was puzzling: 'Another universe seen by astronomer.' And a quote from Hubble barely explained its significance: 'It is a matter of considerable importance that familiar relations are found to be consistent when applied to the first system definitely assigned to the regions outside the galactic system.'

With even that apparently not newsworthy enough, the short report wrapped up by noting two further astronomical

events that also occurred the previous day – discovery of a comet in the constellation Hydra, and the falling of a large meteorite on a farm in Missouri, making a hole in the ground four feet across.

Why so little fanfare? From a news perspective, publication of an academic paper – even a transformative one – was not going to affect most people's lives. It's hard to make a result based on years of work sound as exciting as a sudden discovery or event, like a meteorite strike. But the sheer incomprehensibility for most people of Hubble's finding might have played a part. Twentieth-century physics was moving at a rapid pace. And it was about to make astronomy and descriptions of the Universe increasingly abstract, and harder to relate to.

The American public might also have had its eyes on other things, like the rapidly growing and industrialising economy. Hubble's remarkable advance was made possible by his access to a state-of-the-art telescope that cost the equivalent today of billions of dollars, paid for by wealthy philanthropists with an interest in science. This influx of money is what gave US astronomers an edge over their rivals when it came to examining very faint celestial objects like distant galaxies.

For instance, the hundred-inch Hooker telescope used by Hubble at Mount Wilson Observatory, which was the world's largest from 1917 to 1949, was named after its benefactor, ironworks owner John Daggett Hooker. The Observatory itself was founded in 1904 by solar astronomer George Ellery Hale, the son of an affluent merchant. Funding came from the Carnegie Institution of Washington – a philanthropic foundation set up by US steel magnate Andrew Carnegie to support scientific research.

Lick Observatory, the world's first permanently occupied mountaintop observatory near San Jose in California, was constructed between 1876 and 1887 to host the largest, most powerful telescope built at that time. The money for it (equivalent to around \$20 million today) was bequeathed by James Lick, who was the richest man in California when he died.

Such gifts keep coming today. The twin giant Keck telescopes on Hawaii, whose ten-metre-span mirrors were the largest in the world when they were installed, were constructed in the 1990s using \$140 million in private grants from the W. M. Keck Foundation, which supports scientific research in the US and was founded in 1954 by oil magnate William Myron Keck. The Allen Telescope Array, a radio telescope in northern California that became operational in 2007, has been developed using donations of more than \$30 million from Paul Allen, co-founder of Microsoft.

Some of these benefactors were interested in science themselves and wanted their millions to go to good causes. But perhaps they also wanted some of the rush of big science and cosmological discovery to rub off on them, or at least to build a monument of significance. In his later years, for example, James Lick looked for other ways to spend his money. Plans to build statues of himself or even a giant pyramid in downtown San Francisco were scratched when he was persuaded instead to establish the observatory now named after him. His body is buried beneath one of the domes.

Still, those early philanthropists would not have believed the discoveries that their instruments would go on to make possible.

Our galaxy

A century on from Hubble's breakthrough, we now know that the Milky Way is a galaxy with features a lot like those that astronomers see in the Andromeda spiral nebula. In the middle of the Milky Way is a dense core or 'bulge' of stars, which is slightly elongated into a 'bar'. Four loose-wound spiral arms flow out from the edge of the bar, and sweep through a warped disk of gas, dust and stars. A spherical 'halo' of stars and globular clusters encases the whole.

As the arms turn, they stir gas clouds in which new stars form. On the whole, most stars start their lives being blue and bright, then fade and turn redder as they age. The Milky Way's central bulge is filled with mostly old, red stars; the spiral arms glow blue owing to the creation of fresh young stars.

Look deeper, though, and there's a lot more to the Milky Way than its spiral structure. It's full of anomalies, which tell us about our galaxy's past. For example, astronomers have found pockets of stars with distinct colours which seem to stick out from the rest. Some of these are thought to be remnants of small nearby 'dwarf' galaxies that have fallen at some time into the Milky Way and been swept up by it, like stirring melting cheese through soup. One such ribbon of stars, for example, lies about 30,000 light years away in the direction of the constellation Virgo.

Our galaxy is in turn part of a group of at least fifty more galaxies, stretching for millions of light years. Andromeda is the largest companion, roughly twice the size of the Milky Way. The Large and Small Magellanic Clouds are part of our neighbourhood too, relative galactic dwarfs of billions of stars lying 160,000 and 200,000 light years away,

respectively. That's close enough for streamers of hydrogen gas from them to be pulled into the Milky Way, stripping and starving these modest galaxies of their future star-forming fuel. This vast Magellanic stream of gas stretches across one quarter of the sky.

The Milky Way is slowly cannibalising its neighbours as it moves. Astronomers predict that in 5 billion years or so the Milky Way and Andromeda galaxies will collide. As each rips the other apart, it is likely that they'll destroy their neat spiral arms and merge into an unstructured ellipsoidal mass of stars – a form known as an 'elliptical' galaxy. The tens of dwarf galaxies beyond will be slower to be drawn in but will also eventually succumb to gravity's force.

What else do we know about the Milky Way? Current estimates put the diameter of our galaxy at around 100,000 light years, with a disk that's just 1000 light years thick. It contains between 100 and 400 billion stars. The Sun, which lies about 28,000 light years from the galaxy's heart, is rotating about that centre point at a speed of around 800,000 kilometres per hour. Even so, it takes us about 230 million years to go once around.

The Milky Way is also almost 14 billion years old. How do we know? Astronomers have searched for the oldest stars within it, which mainly lie in the outer halo. In general, researchers believe that this part of the Milky Way formed first, with the disk forming a billion years or so later. There are many different types of stars, and astronomers have mapped out their typical lives. Massive stars, tens of times bigger than our Sun, burn bright and hot but also burn out quickly, over mere tens or hundreds of millions of years. Smaller stars can fizz away for longer.

The first stars are expected to have formed from relatively pure forms of gas – mainly hydrogen with a smattering of

helium and light elements. When these reach the end of their lives, they explode as novae or supernovae. The core region of the star collapses under its own gravity as there's not enough heat to support it. The outer layers are blasted off in shells of gas. But these shells contain all the other elements that the star produced during its lifetime, which include heavier elements like nitrogen, oxygen, silicon, iron and more.

Stars burn via nuclear fusion – atoms of light elements like hydrogen and helium are compressed so hard inside the star that they fuse together, releasing heat. This process gradually builds up elements across the periodic table, at least up to iron, whose atoms are relatively stable. Elements heavier than that are produced in further ways, including in the blast waves of supernovae: stars really are chemical factories.

When stars die, they spray their heavier elements across space, and these elements go into gas clouds, where new generations of stars form. Thus, the earliest stars should lack these heavy elements, which did not exist when they formed. Astronomers have searched high and low for such pristine stars and today several thousand are known within the Milky Way. But there's a twist.

Not all these ancient stars are in the halo: some are sitting within the galactic disk. Perhaps the disk and halo formed at the same time or, as some astronomers now think, many of these might be interlopers, either pulled into the disk aeons ago, or immigrants drawn in from past galactic mergers. Far from being a settled system, the Milky Way is a dynamic place, its stars and gas clouds being constantly stirred and fed by its companions. What exactly lies beyond the Milky Way? Back at Mount Wilson Observatory in California, Edwin Hubble and his colleague Milton Humason turned the

powerful Hooker telescope again towards the distant spiral nebulae, measuring accurate Doppler shifts for as many objects as they could.

One thing they wanted to explore was a finding a decade earlier by Vesto Slipher at Lowell Observatory in Arizona. Slipher had showed that, while a few spiral nebulae, including Andromeda, had characteristic markers in their light shifted to the blue - implying they were approaching us, the majority had those markers shifted to the red end of the spectrum, suggesting that most of the nebulae were instead moving away from Earth. And quickly - often at speeds exceeding those of any star in our Milky Way (more than 1000 kilometres per second). With the powerful Hooker telescope, it was possible to look at more than Slipher had managed.

And Hubble soon began to notice something else - that the smaller, fainter galaxies tended to be the ones moving away the fastest. This relationship, which he published in 1929, is now known as Hubble's Law. And the slope of the line - the rate at which galaxies are receding from us as a function of distance - is known as the Hubble Constant. Both have been crucial to understanding the nature of the distant Universe.

This time Hubble's results really did cause a storm. As we now see it, what Hubble had found was evidence not only that galaxies are rushing away from us but that they are also moving apart from one another - that space itself is expanding. Gravity holds close galaxies that are nearby, including Andromeda, the Milky Way's partner. But galaxies beyond our Local Group are flying apart with increasing speed the farther way they lie. This was, and is, simply mind-boggling.

Before then, the consensus was that the Universe was 'static' – meaning that, as a whole, it looked pretty much the same at any given time. Writ large, it had always been this way, and it always would. Galaxies might move about or collide occasionally, and stars formed in gas clouds and burned through their life cycles, but otherwise the run of cosmic events was steady. Looking out into space was like looking into the deep sea – hard to fathom, with much going on and full of discoveries, but a set piece.

Physicists struggled at first to explain Hubble's results, even in a way that made sense mathematically – how could spacetime inflate like a balloon? Even Albert Einstein initially thought this way. In the run up to 1915, Einstein had risen to fame for his theories of special and general relativity – the physics of space and time. These theories showed, for example, that the three dimensions of space and one of time could be described mathematically in four dimensions of 'spacetime'. The force of gravity arose from the curvature of spacetime, making bodies move like a ball would when rolling down and up hills. But there was no need for a repulsive force to counter gravity, or to fling bodies apart, in Einstein's equations.

It took another year or so before physicists found equations and explanations that worked, largely through the efforts of Belgian astronomer and priest Georges Lemaître. In 1931, Lemaître described the present Universe as the result of an explosion of some sort of primeval atom – the 'ashes and smoke of bright but very rapid fireworks'. Lemaître's 'fireworks theory' presaged our modern 'Big Bang theory' of the origin of the Universe. It was soon accepted as a description of what was going on, although debates about the cause and nature of the explosion and veracity of the expansion would continue for decades.

Another conclusion that follows from galaxies flying apart is that in the past they must have lain closer together. Perhaps, long ago, they might even have come together at a single crunch point. Drawing back the line from Hubble's chart implied that the Universe might be billions of years old and might have had a distinct beginning. Today, from measurements of the expansion and other evidence, including Cepheid variable stars, astronomers estimate that the Universe is around 13.8 billion years old.

Hubble's discoveries came at a time when other areas of physics were also developing fast. Down at the scale of atoms, a surge of fresh knowledge soon began to transform astronomy, along with the world. Putting these advances together led to a new science of the Universe as a whole, cosmology. And the picture that has gradually emerged of the cosmos is discombobulating. Modern astronomy has become more mathematical than intuitive, challenging us to really analyse and comprehend the Universe we inhabit, not just be wowed by it.

Modern physics

At the dawn of the twentieth century, subatomic particles had just been identified. The existence of the electron – a particle with a negative charge, around one thousand times lighter than the lightest atom – was inferred in 1897 by Joseph John (known as J. J.) Thomson to explain the behaviour of electricity. And in 1919, Ernest Rutherford unearthed the proton, a particle more massive than the electron that carries equal but opposite charge and sits within the dense core or nucleus of atoms. In 1932, James Chadwick spotted the neutron – a particle with a mass similar to the proton but no electrical charge, which is also

found in an atom's core - and completed our basic understanding of the atom.

Combinations of all these particles could thus describe the properties of different atoms. Together, the number of protons and neutrons in the atomic nucleus set the mass of the atom. Hydrogen is the lightest element, comprising one proton and one electron. Helium is the next lightest, comprising two protons and two neutrons, plus four balancing electrons. Heavier elements contain proportionately more of each. Physicists were able to order and group elements according to these weights and the numbers of protons and neutrons they carried.

Physicists then went on to show that firing neutrons at atoms could cause their nuclei to disintegrate, forming other elements in the process. For example, shooting a neutron at a nitrogen atom could kick out a helium nucleus and leave behind the core of a boron atom. By 1939, Lise Meitner and Otto Hahn had found that firing neutrons at uranium could split that heavy element into lighter ones - a process known as nuclear fission. As history attests, this knowledge eventually led to the harnessing of atomic power and the atomic bomb, which was dropped to devastating effect on two Japanese cities, Hiroshima and Nagasaki, killing more than 100,000 people at the end of the Second World War in 1945.

Pioneers of this emerging physics of the atom were also keen to apply their know-how to challenging puzzles in astrophysics and cosmology, from the origin of the elements and how stars shone to the physical nature of the Universe. For example, in the 1930s, Soviet-American physicist George Gamow imagined how the physics of atoms and radiation might have operated in the hot, dense conditions of the early Universe to form chemical elements from

scratch, atoms of which went on to agglomerate into stars and galaxies.

Gamow had spent his early career in Odessa and Leningrad trying to understand why the atomic nucleus was so confined and why it broke apart under radioactive decay. After being denied official permission to attend a conference in Italy in 1931, he tried to defect from the Soviet Union with his wife – including attempts to kayak over the Black Sea to Turkey and from Murmansk to Norway. Poor weather thwarted them. But in 1933 he was allowed to attend a physics meeting in Brussels, after which he arranged to work temporarily in Europe before moving to the US in 1934.

Gamow set his PhD student Ralph Alpher to work out the mathematics of the early stages of the Universe, based on Lemaître's 'fireworks' model. Their theory presumed that when the Universe was very young it was so hot and dense that atoms would not hold together. The Universe was a sea of primordial stuff, which they called 'ylem', after a Middle English or Old Hebrew word meaning 'first substance out of which everything is made'.

This original substance consisted of a scorching soup of photons, electrons, protons and neutrons. All the particles whirled so fast they crashed into one another. As the Universe swelled it cooled and the rate of collisions slowed. Eventually hydrogen atoms formed, and protons captured neutrons to make atomic nuclei of increasing weights – first heavier forms of hydrogen such as deuterium (comprising one proton and one neutron) and then gradually helium and other light elements like lithium and beryllium.

Their findings did a good job of explaining the proportions of hydrogen and helium in stars – three parts hydrogen to one part helium. But they failed to explain the existence of

other heavier elements, such as carbon, nitrogen and oxygen, let alone iron or uranium.

Alpher and Gamow published their work in a 1948 paper. Known for his sense of humour, Gamow inserted a third author, Hans Bethe, between their names as an intellectual joke – to make the list of authors sound like the first three letters of the Greek alphabet (alpha, beta, gamma). Bethe was a real person, an eminent physicist and friend of Gamow, who agreed to sign the paper and support its ideas.

Gamow's creative imagination prevailed throughout his career, including in books and articles he wrote for the popular press to explain the mind-boggling concepts of the emerging science of atoms and space. Rather than simply publishing scripts of lectures, as most other scientists did, Gamow deployed a fictional character called Mr Tompkins – an ordinary bank clerk with a keen interest in science – to ask the questions on everyone's lips.

For instance, Mr Tompkins experiences living in different types of inhospitable Universe, from a confined one, which seems like sitting within a spherical mirror, where rays of light can travel right around the curves of spacetime to come back to you, to others where areas alternately expand and contract. What a relief he says, to live in an expanding Universe, where views go on forever!

In one story, called 'Cosmic Opera', Mr Tompkins enjoys arias from none other than George Lemaître and Gamow himself. Lemaître sings of how his primordial atom shatters into myriad galaxies; praise the Lord! Gamow splits hairs with the Belgian priest, singing that the origin was in a 'neutron fluid, not primal atom as you told'.

The third aria comes from another astronomer, who suddenly materialises from empty space pulling a newborn galaxy from his pocket. 'The ageing galaxies disperse, burn

out, and exit from the scene. But all the while, the Universe is, was, shall ever be, has been. Stay O Cosmos, O Cosmos, stay the same! We the steady state proclaim!’

The third showman being portrayed was Fred Hoyle, a British astronomer based at the University of Cambridge. Hoyle and his colleagues Thomas Gold and Hermann Bondi had worked closely together on radar during World War 2. They weren’t convinced by the prevailing idea of an expanding Universe; to them, it seemed too far-fetched.

In a radio lecture in 1948, Hoyle described the concept of the Universe as having exploded out from a single point in space and time in some kind of ‘big bang’ as unrealistic. Thus, while attacking, he unwittingly coined that phrase, which eventually stuck, first in the public imagination and only later as a term within astronomy itself. It was as uncivilised as a party girl jumping out from a birthday cake, he once said.

The explosion was too quick, Hoyle reasoned, to allow enough time for everything we see around us to form. Hubble’s early estimates had put the age of the Universe at less than 2 billion years old, but by then scientists knew from rates of radioactive decay in rocks that the Earth was older than that (we now know it is 4.5 billion years old). And complex life also needed time to form. Creating people, plants and planets out of a vast fireworks explosion all seemed too sudden and chaotic.

Hoyle, Bondi and Gold hit upon a different idea – the ‘steady state Universe’. In their model, the Universe had gone on and would go on more or less as it is forever, as with the static Universe. But, in places, their theory allowed for new stars and galaxies to pop into existence. Space nearby would need to expand to accommodate them – thus explaining the rush of galaxies away from our own. The

creation of matter was possible, the trio reasoned, since Einstein's work on relativity had showed how matter and energy are equivalent (as summarised in Einstein's famous equation $E = mc^2$). This opened up the possibility of particles being created from pure energy in empty space.

According to Hoyle, the 'steady state' idea came to them after watching a horror film, *Dead of Night*, at a cinema in Cambridge. The film was split into parts, each acting out a repeating nightmare. Gold apparently suggested that such a film could be run continuously, so that you could step in and watch it from any starting point. Might the Universe also be like this, he wondered, an endless loop? Hoyle, Bondi and Gold set about calculating what this would look like.

Meanwhile, Hoyle also turned his mind to the origin of the elements in stars. His later collaboration with Willy Fowler and Geoffrey and Margaret Burbidge culminated in a landmark 1957 paper titled 'Synthesis of the elements in stars', which astronomers still refer to by the initials of the authors' surnames: BBFH or B²FH. This paper set out how elements are formed in sequences of nuclear reactions, up to iron, which has a stable nucleus (it's now known that elements heavier than iron are formed in other ways, such as through violent supernova explosions).

For example, in the hot, dense interiors of stars, carbon nuclei may fuse to produce neon, sodium, magnesium or oxygen. Oxygen burning can lead to silicon, phosphorus or sulphur. Eventually, out of these stellar furnaces, other elements like chlorine, argon, potassium and calcium also arise. Such cascades explained a lot, though they didn't explain where the original hydrogen and helium that kicked off the whole process came from.

And so, by the 1960s, physicists offered convincing explanations for how the elements formed, and where

atoms came from. Galaxies were receding from us, impelled by some initial cosmic force, whilst gravity's attraction led stars to cluster and burn hydrogen within their dense inner fires. Astronomers mostly agreed that the Universe is dynamic and always changing. But the underlying concepts were still a little untethered. Competing stories led some scientists to criticise the new cosmology as 'not very scientific'.

Choosing an underlying cosmic theory during this period was essentially an aesthetic choice, or a philosophical belief: there was very limited evidence to go on. Some astrophysicists argued that trying to describe the Universe's entire history was a challenge too far, beyond what science can achieve. What was there before the Big Bang? No-one could say; the question did not even make sense. But then how might matter be continually created in the space between galaxies, as Hoyle's coterie believed? It seemed possible, to a generation that had witnessed the atomic bomb and the birth of nuclear energy, but no-one could say exactly how or why these particles suddenly jumped into existence, or why they had always done so.

Others saw in the emerging science of cosmology justifications for their own beliefs. For example, in 1951, Pope Pius XII marvelled at how 'along with matter, there burst forth from nothing a sea of light and radiation, and the elements split and churned and formed into millions of galaxies' – clearly, as he saw it, proof of the existence of God. Communists in the Soviet Union and China settled on the opposite: a Universe infinite in size and age and make-up, needing no creative act, was preferable from their atheistic perspective.

But, as points of connection between rival theories were gradually explored over the following decades, the balance

tipped in favour of Big Bang models. The abundance of helium in the Universe was one crucial data point. Observations revealed that helium is about one third as common as hydrogen, in places as diverse as the Orion nebula and the Sun. This ratio was close to what Alpher, Robert Herman and James Follin predicted would have formed within the hot, dense conditions of the early Universe. All gas everywhere started with this basic composition, before elements formed in stars polluted it.

Other lines of evidence soon followed. These came from the opening of a new window on the Universe – detections of radio waves from the cosmos, which revealed a very different kind of ‘static’ Universe. Sides of the Universe that had hitherto only existed as mathematical formulations became evident. The modern Universe would turn out to be made of far more than matter.

Radio astronomy

While radio waves (low-frequency electromagnetic waves) were discovered in 1887 by German physicist Heinrich Hertz, it took decades more for receivers to be turned upwards to point at the skies. Early efforts to try to detect radio waves from the Sun failed, some perhaps from sheer outlandishness. Thomas Edison, for example, planned to deploy a massive pile of magnetic mineral ores to pick up changing electrical signals from the Sun.

The switch in telecommunications technologies in the 1920s, from transmitting Morse code signals to carrying voices, demanded improvements such as removing electronic hiss and static. And figuring that out was Karl Jansky’s job, working for Bell Laboratories’ field site in Holmdel, New Jersey. In August 1931, he picked up a

strange source of weak static that seemed to follow the same path across the sky each night. Early in the evening, it came from the southeast, at midnight from the southwest, and before dawn from the west.

Jansky put it down to thunderstorms, but the strange hiss from the skies persisted and began to whisper into Jansky's earphones at different times of day. By January 1932, he realised that it was a continuous hum, shifting direction and 'going completely around the compass in twenty-four hours'. He wondered if it came from the Sun, but it didn't always line up. It was even unchanged during a partial eclipse, proving it was not a solar phenomenon.

Plotting out how the signal's position changed through the year, Jansky realised, with the help of a colleague who had an interest in astronomy, that it was coming from a particular point on the sky – the centre of the Milky Way galaxy. In 1933, he published his finding in a paper modestly titled 'Electrical disturbances apparently of extraterrestrial origin'. The *New York Times* splashed the discovery on their front page – with a caution to potentially worried readers that there was 'no evidence of interstellar signaling'.

Thereafter, not much happened for a few years. Astronomers were used to using telescopes and didn't know much about radio technology, which was the domain of engineers. The next step came from the son of a jam-factory owner in Wheaton, Illinois. Grote Reber was an amateur radio enthusiast who studied electrical engineering. He became fascinated by Jansky's 'cosmic static' and set about trying to build a machine himself to measure it.

Reber came up with the idea of using a parabolic giant dish to collect and focus radio waves from space onto a central receiver. In the summer of 1937, Reber began to build the radio telescope in his own backyard. The nine-

metre-wide dish was made from steel plates, mounted on a curved wooden frame attached to concrete piers. The dish could be swung to the north or south using a hand crank linked to the axle of a truck. The whole thing stood fifteen metres high. Locals speculated that it was some top-secret military installation, or a water collector. Reber's mother hung out her washing on it, kids climbed on it and rhubarb apparently grew nicely below.

Diligently, Reber tuned his dish antenna and set about mapping signals from across the whole northern sky, as various regions drifted over the telescope. The picture he produced was striking - he captured the contours of the Milky Way and noted a few bright spots in the directions of the constellations Cygnus, Cassiopeia and Canis Major. He succeeded in detecting radio waves from the Sun.

A decade or so later, after World War 2, further studies of the radio sky in the 1950s showed that the bright spot in Cygnus (duly named Cygnus A) was a compact source of radio emissions distinct from the Milky Way. This finding propelled others to look for more such 'radio stars', including groups in Cambridge, UK, and Sydney, Australia.

In Australia, John Bolton and others began to pin down the locations of the radio sources and look for visible counterparts on photographic plates. There were no obvious bright stars that were consistent. But eventually they began to associate some of the radio sources with gas clouds or nebulae - Taurus A was linked with the Crab Nebula, the ejected shell of a supernova whose explosion 900 years ago was recorded by Chinese astronomers. Virgo A seemed to be associated not with one star but with an entire elliptical galaxy known to be millions of light years away. The radio sources were turning out to be a mixed bag.

Meanwhile, on the other side of the world, Martin Ryle's team at the University of Cambridge's Cavendish Laboratory and Bernard Lovell's at Jodrell Bank near Manchester were doing much the same. At the Cavendish, a thrifty spirit of experimentation had been instilled by groundbreaking physicists of earlier eras, including atom pioneer Ernest Rutherford. Using arrays of simple wires as collectors attached to posts in nearby fields, and combining their signals electronically, Ryle and his colleagues developed a technique for pinpointing the positions of radio sources more accurately.

By 1953, around 200 radio sources were known. The next year, Ryle proposed that radio sources might be used to test cosmological models. If Hoyle's steady state Universe held, then there should be an infinite number of radio sources, looking progressively fainter the farther away they were, in a predictable way. The Big Bang model would produce a different distribution.

In 1961, Ryle presented clear data ruling out Hoyle's model. And it wasn't long before more evidence secured the Big Bang's status even more impressively. In 1964, Arno Penzias and Robert Wilson, two physicists at Bell Labs in Holmdel New Jersey – where Jansky had previously worked – picked up the faint signal of heat left over from the early Universe.

This heat was evident as a faint glow at microwave frequencies, just as Alpher, Herman and Gamow had predicted. They didn't know what it was at first – again, it appeared as static that wouldn't go away. The signal seemed to be coming from all over the sky, even away from the Milky Way. At first, so the story goes, Penzias and Wilson wondered if it might be pigeon droppings clogging the horn antenna that they were working with. But a group of

physicists down the road at Princeton, led by Robert Dicke, inadvertently heard of the static noise issue and put two and two together.

When the Universe was very young, they concluded, and too hot for atoms to form, it was a soup of radiation and particles. Light ricocheted off these charged particles in a sort of fog. Only when the Universe cooled to the point at which hydrogen atoms formed, around 400,000 years after the Big Bang, could light escape. Since then, as the Universe has expanded, the wavelength of that light has been stretched, such that today it still gives off a little radiation at long wavelengths in the microwave part of the spectrum. This heat is essentially akin to the dim glow from a coal with a temperature of a few degrees Celsius above absolute zero (the lowest temperature that's theoretically possible). By detecting that signal – known as the cosmic microwave background – Penzias and Wilson had vindicated another prediction of the Big Bang model.

Even so, Hoyle and the steady state stalwarts didn't bow immediately. Indeed, for the rest of their careers some astronomers, including Hoyle, remained sceptical of Big Bang theory. Undoubtedly, novel science needs its questioners. But a slew of further discoveries since have continued to support basic Big Bang theory, even if they have opened up even deeper philosophical questions about the Universe's origins.

Little green men

Radio astronomy would soon deliver more surprises. In 1967, a graduate student at the Cavendish Laboratory, Jocelyn Bell Burnell, spotted regular radio flashes whilst she was using their rudimentary telescopes – one thousand

poles strung with nearly two hundred kilometres of wires across an area bigger than fifty tennis courts. After seeing regular pulses coming from one part of the sky, she switched to a better recorder. 'For a month it recorded nothing, and then one day, on 28 November 1967, it came again, a string of pulses one-and-a third seconds apart,' she later recalled in an after-dinner speech.

The regularity of the signals was puzzling at first. Jocelyn joked: 'occasionally there would be something I didn't recognise and I'd record it with a question mark or, as a joke, LGM for Little Green Men.' It wasn't entirely a joke: astronomers did take seriously the possibility that this was an intentional communication and, just to make sure, they checked carefully for any signs that the sender of the signal was on a planet orbiting a distant star. If it had been, then the signal would shift back and forth in frequency a little. It did not.

Bell Burnell and her supervisor Tony Hewish wrote up their intriguing results in the scientific journal *Nature*, including a brief mention that at one stage they had thought the signals might be from another civilisation. 'When the paper was published the press descended,' Bell Burnell recalled, 'and when they discovered a woman was involved they descended even faster.' She described how she had her photograph taken 'standing on a bank, sitting on a bank, standing on a bank examining bogus records, sitting on a bank examining bogus records: one of them even had me running down the bank waving my arms in the air - Look happy dear, you've just made a Discovery!'

These regular radio bleeps turned out in fact to be made by a type of star called a 'pulsar'. Magnetic fields on its surface produce a beam of radio waves, which spins with the star like that from a lighthouse.

I love reading Jocelyn's account as I too used to manage a small radio telescope at Cambridge University. This was much later in the 1990s and it looked very different – a ten-metre-wide T-shaped aluminium turntable with three basket-sized horns pointing skywards. The whole thing sat inside a shallow, angled aluminium fence, designed to block static from mundane electrical sources on Earth.

On a sunny day the light and heat reflected from all these metal surfaces was intense, while in winter I scraped off the ice and snow. I still recall the sound of the machine – a steady pulse of hisses and clunks from the cooling system for the receivers. I used to drive out of town to the telescope site at Lord's Bridge each morning to download data and check the telescope was working, sometimes having to scramble beneath the turntable to try to fix it.

I enjoyed the freedom of escaping the lab and getting out into the Cambridgeshire countryside, often listening – illicitly so, it seemed then – to the Woman's Hour programme on BBC Radio 4. The radio astronomy group at the Cavendish laboratory still showed its wartime roots – with Morse code signals used to announce tea breaks (dit dah dit dah dit dah) and to call individuals out of their offices to meet people in the stairwell. There were very few women in the group back then, just a handful, and I seemed to quite regularly bump into Jocelyn in UK astronomy meetings where I'd been rolled out as a representative. 'Hello, it's you again,' she said with a grin, when we found ourselves yet again the only two women in a room full of men.

The Cosmic Anisotropy Telescope, as it was called, was a bespoke instrument for making images of the cosmic microwave background. It was trying to search for finer structure in the bath of radiation from the Big Bang that Penzias and Wilson had revealed. It succeeded – in finding

slightly warmer and cooler spots in the background, tinted red and blue in the maps we produced. These spots were of a finer grain than other efforts had then managed, albeit over a small patch of sky.

A few years earlier, the COBE (Cosmic Background Explorer) satellite had published its map of larger hot and cool spots across the whole microwave sky, setting another milestone. On 24 April 1992, the *New York Times* described COBE's map as 'a momentous discovery' - 'astronomers looking back toward the beginning of time have detected broad wrinkles in the fabric of space.' I was in Australia at the time and remember attending a rushed meeting of astronomers in Canberra to pore over the results. Everyone was gob-smacked by how it all stacked up.

Several things were striking about that map. First, broadly speaking, the spotty patterns in the cosmic radiation look much the same in all directions across the sky, once the motion of Earth and emissions from the Milky Way have been compensated for. This implies that all regions somehow 'know' about the others. They must have been connected by signals travelling at the speed of light farther back in time when the cosmos was far smaller.

The temperature anomalies recorded by the space telescope were also relatively tiny - of no more than one hundred-thousandth of a degree, compared to the background's temperature (now precisely known to be 2.7 degrees Celsius above absolute zero). But these hot and cool spots were profound.

As the *New York Times* reported, 'their discovery is the first evidence revealing how an initially smooth cosmos evolved into today's panorama of stars, galaxies and gigantic clusters of galaxies.' Each spot marks a region that was slightly denser or under-dense at the time when the

radiation was liberated 400,000 years after the Big Bang. As gravity pulled clumps of matter together, these seeds would grow into the varied Universe that we see around us today.

Since COBE, other space telescopes, including WMAP and Planck, and some on the ground, have discerned even finer details of this baby picture of the Universe. So far, all that has been seen is just as theorists have predicted for the Big Bang model. It's impressive, if also a bit spooky or almost disappointing, not to find anything radically new, although there are some inconsistencies still to iron out amongst different experimental results. But there's much more to look at beyond the microwave sky. The complexity of the cosmos is as vast as our understanding of it is limited. And some objects, like black holes, defy even our best theories.

Black holes

In 1963, radio astronomy produced another surprise. At Palomar Observatory near San Diego in California, Maarten Schmidt was trying to use the Hale Telescope – at that time the world's largest, with a mirror twice the diameter of the one Hubble had used – to measure the spectrum of a faint blue star. The star lay near the position of a bright radio source, which had been noted in a catalogue compiled by the Cambridge group. Schmidt wanted to identify it, to learn more about these diverse radio sources. Astronomers had dubbed such objects 'quasi-stellar radio sources', or 'quasars' for short.

Schmidt managed to collect light from the star. But when he examined it, the spectrum looked like nothing he'd seen before. Eventually, he realised that there were familiar features there, including a series of characteristic frequencies emitted by hydrogen. But they were moved far

to the red and smeared out: this 'star' seemed to have a redshift that put it at similar distances to the spiral nebulae.

The fact that something that looked like a star was so bright yet so remote was a real puzzle. It was as if all the light from all the stars in one galaxy had been concentrated in one point. How could it be so luminous? A handful of other quasars were soon identified, as well as some that lacked radio emissions, and were known simply as 'quasi-stellar objects'. Once it became possible to look at quasars at many different frequencies, it became clear that they were unlike stars. Their brightness extended right across the electromagnetic spectrum, from radio waves to X-ray and gamma rays. But how did they produce so much energy in such a small space?

Astronomers' minds turned to the most powerful cosmic force they knew - gravity. And, in particular, to black holes. A black hole is a region containing so much mass that it distorts spacetime to the extent that not even light can escape. Imagine throwing a ball up in the air - gravity pulls it back to Earth. Throw the ball faster and it reaches higher. If it can be shot up fast enough - in a rocket, say - then it can be held in orbit around Earth.

The velocity at which the ball must go to not fall back is known as the escape velocity, and depends on the mass of Earth. If Earth was more massive, the ball would need to travel faster to escape. A black hole is so massive that its escape velocity exceeds the speed of light: nothing can ever escape from it. It's a black bottomless pit in the cosmos whose interior is shut off from us.

But black holes do affect what lies around them. And in the case of quasars, the black hole in question sits at the heart of a distant galaxy. The bright glow doesn't come from the black hole directly, but from the churning mass of gas

and dust just outside. As material is pulled in towards the black hole, it collects, collides and heats up until it glows fiercely.

Columnar jets of particles can also be driven off, bound and accelerated by magnetic fields around the black hole. These jets can extend for millions of light years, well beyond the galaxy's stars, and may glow at radio wavelengths. These jets, which end in pools or 'lobes' of ejected particles, are what radio astronomers can see.

My own PhD studies focused on trying to understand how quasars worked and what they looked like in three dimensions. Astronomers aren't like other scientists: they can't visit or prod and poke the subjects of their research. They can only observe them from afar and try to infer what is going on by looking at many objects. And in quasars, much of the machinery is hidden by vast clouds of gas and dust – the same sort of clutter that obscures our view of the Milky Way. Similarly, when we view a quasar side on, much of the brilliant light is obscured. We get the clearest and brightest view when we look at the galaxy face on, where the murk is thinner.

The sorts of black holes that drive quasars are huge, with masses millions or even billions of times that of our Sun. We now know that almost all galaxies have such supermassive black holes in their centres, with typical masses of a few percent of that of the galaxy that hosts them. Even our own Milky Way has a resident central black hole, with a size equivalent to 4 million Suns.

In most galaxies, the central black holes are dormant: only a fraction appear in an active, radiation-emitting state where they might be seen as a quasar. Astronomers think that this activity might be intermittent, with the central black hole affecting how stars form across the rest of the

galaxy as it variously sucks in gas and blasts it out. Black holes might have affected how all galaxies look and how they form and evolve, but astronomers still have a lot to learn about how this works.

The concept of a black hole was first envisaged, remarkably, in 1783 by an English country parson, John Michell. Trained in mathematics and geology, Michell was interested in gravity, and how it held some stars together in pairs. Trying to come up with ways to measure the mass of a star, Michell imagined particles of light coming from its surface. Just as satellites must exceed some velocity to escape Earth's pull, fast-moving light would flow out. But if the star became more weighty, it would hold the light back, Michell mused. And for a really massive star, light might not manage to escape at all. The star would be invisible to an outside observer.

A more modern take on what that would look like came in 1915. One year after Einstein had published his theory of general relativity, German physicist Karl Schwarzschild solved those equations for the case of an object so massive that light could not escape from it. Spacetime warped so tightly around the massive spherical space that light beams wound around it. The surface where this happened is known as the 'event horizon'.

Schwarzschild reached this conclusion while fighting in a trench on the Russian front in the First World War. He sent his solution to Einstein in a letter: 'The war treated me kind enough, in spite of the heavy gunfire, to allow me to get away from it all and take this walk in the land of your ideas,' he wrote. But, unfortunately, Schwarzschild didn't live to continue this conversation. He succumbed to a rare skin disease the same year and died.

His idea was taken up, though, and physicists suggested that such an object might result from the collapse of a massive star. Once such a star burns up its nuclear fuel, its outer layers are no longer held up, and they start to collapse. All the material in the star falls inwards towards the core.

As we have seen, stars with modest masses like the Sun eventually stop shrinking as the matter within them is supported by forces within atoms. They appear small and dim, as white dwarf stars, in which all the material within the Sun is contained in a space the size of Earth.

A little larger in the first place and they can crush down a little more, to form neutron stars, where all the protons and electrons merge to form neutrons. These are incredibly dense, such that the Sun's mass would be squeezed into a space the size of a city. A sugar-cube-sized chunk of such material would weigh as much as a mountain.

But with a star more massive still, and even these atomic forces are overwhelmed. If there's nothing left to support the star, all its matter will condense down to a single point, or singularity. While the stuff of the star effectively disappears, by the rules of Einstein's theory of general relativity, its mass still distorts space and time around it, and so it appears as a black hole.

To someone looking on, time slows to a stop at the edge of the black hole. Something falling in would appear frozen in time. Just before it hit the event horizon, though, it would be stretched and scrambled – spaghettified, as even physicists put it – by the extreme gravitational forces. No-one knows what happens exactly within the black hole, especially at the singularity. In theory, time itself should vanish. Certainly, nothing that goes in can come out again.

The name 'black hole' was taken up by American physicist John Wheeler after a conference talk in New York in 1967, where it was apparently shouted out from the audience. As he later put it beautifully in his autobiography, the black hole teaches us 'that space can be crumpled like a piece of paper into an infinitesimal dot, that time can be extinguished like a blown-out flame, and that the laws of physics that we regard as "sacred", as immutable, are anything but'.

Black holes sound hypothetical. They often feature in science fiction, as terrifying natural hazards, or as portals to parallel dimensions or other parts of the Universe. But there is evidence to support their existence. In the 1970s, astronomers began to look for X-rays coming from stars. In one of the brightest cases, called Cygnus X-1, they were able to show that this object was in fact a star with a black hole orbiting it – or at least something tiny and invisible that is around ten times as massive as the Sun. The X-rays were given off by material being sucked from the large star on to the black hole.

On a larger scale, astronomers have also tracked the positions of stars and gas clouds travelling close to black holes in the centres of galaxies, including our own. Like comets travelling around the Sun, they speed up as they come near to the hole and are flung out again on elliptical or deflected paths. And, by combining the power of many radio telescopes around the world, astronomers have been able to make an image showing a dark spot at the core of the Milky Way, coincident with its black hole.

Because black holes distort spacetime around them, they also disturb the passage of rays of light coming from stars and galaxies behind. A bit like viewing them through a curved fairground mirror, distant objects projected on the

sky around black holes appear a little stretched. The black hole is said to act like a 'gravitational lens'. In the most extreme case, light from an object lying directly behind a black hole appears smeared out into a circle or ring.

Any massive object does the same thing, to a lesser extent, implying that when we look at any patch of the distant Universe we cannot get a sharp view. Far away galaxies appear as coloured streaks on the sky. But that distorted view can be useful to astronomers, as they can model what the intervening distribution of mass must be that produced the alterations. It's yet another window on the Universe – a gravitational view. And it has also thrown up many surprises, just as looking at radio waves and other parts of the electromagnetic spectrum have.

For example, as stars explode and massive objects careen around the cosmos, smash together or blow up, they stir and stretch Einstein's spacetime fabric and spread ripples, analogous to those from throwing stones into a pond. In 2015, an experiment in the US called LIGO (Laser Interferometer Gravitational-Wave Observatory) detected these ripples, or gravitational waves, for the first time by very carefully monitoring the positions of masses suspended four kilometres apart.

The source of the first gravitational wave they caught was the final inward spiral and coalescence of a pair of black holes around thirty times as massive as our Sun, collapsing together to form a single black hole of around sixty solar masses. As the wave passed through, the masses on Earth shifted by a tiny amount, which is just detectable using lasers. Although they originate in catastrophic cosmic events, the waves are extremely weak by the time they reach Earth. The spacetime fabric of the Universe is stiff but is set aquiver by the motions of celestial bodies.

The presence of gravitational waves has also been inferred from changes in the rate of spinning of some neutron stars, in the form of pulsars. These collapsed stars with strong magnetic fields emit beams of radio waves as they spin, producing regular flashes to an onlooker. If the collapsed star has an irregular surface or companion, it may lose energy as it gives off gravitational waves. Pulsars are also being used as clocks to detect the passage of gravitational waves flowing through our galaxy. Waves between the star and Earth stretch space temporarily and change the rate of ticking of the pulses ever so slightly.

Thus, radio astronomy and other observations have revealed that the cosmos contains much that's unexpected, as well as much that duly follows the laws of physics. Our view of the distant Universe is distorted, while its gravitational spacescape is specked with yawning chasms and shudders from the jolts of crashes and explosions of celestial bodies. And that's not all.

There's far more to the Universe's shadow side. While astronomers through the centuries have looked to pinpricks of light, just like the tip of an iceberg, there's much that's unseen below the glittery surface of the cosmos. And, in this murk, there's much that's unsettling.

Dark Universe

We know that space is filled with clouds of gas and soot, which veil stars and absorb their light. We need to look beyond those in the Milky Way to see others beyond. There's much more cosmic rubble out there too - husks of dead stars and the planets, asteroids and ice-balls whose presence in our own solar system is only given away by

reflected light from the Sun. Each galaxy must have its own hordes of all sorts of celestial bodies, much like ours.

But astronomers now suspect that such familiar forms of matter are themselves just the icing on a far larger dark cake. Through observations of patterns in the cosmic microwave background and other evidence, many lines of reasoning suggest that only 5 per cent of all the mass and energy in the Universe is made up of ordinary atoms composed of protons and neutrons, the stuff that makes up planets and stars and organisms like us. What the rest, the great majority of the Universe's contents, actually is eludes us for the time being, though astronomers and physicists are finding tantalising clues.

The motions of stars and galaxies hint that another 25 per cent lies in a stranger form of matter that doesn't interact with light but reveals itself through its gravitational effects. The need for such 'dark matter' has been known since the early 1930s, when Swiss astronomer Fritz Zwicky recognised that all was not as it should be in a cluster of galaxies in the constellation of Coma Berenices. The swarming galaxies were moving too fast around one another to be held together as a group under their own gravities alone, as judged from the masses of their stars. Zwicky suspected that some hidden material of a type, yet to be discovered, was adding to the cluster's mass.

Decades later, American astronomer Vera Rubin saw a similarly puzzling pattern in the speeds of stars in spiral galaxies. Just as the outer planets move more slowly than inner ones in our own solar system, astronomers expected that the speeds should drop off in the outer regions of these galaxies. But the speeds of stars in the outskirts were just as high as those closer in. 'What you see in a spiral galaxy,' Rubin concluded, 'is not what you get' – meaning that the

stars did not give away what the underlying substance of the galaxy was.

The stars were behaving as if there was some other type of matter dominating their motions – with a mass ten times as much as that of the stars. In other words, 90 per cent of the mass of these galaxies was in unseen dark matter. It was not normal gas, as it did not glow or absorb light from background galaxies. It was entirely invisible. But the Universe was full of the stuff. And even today, astronomers still don't know what it is. They've postulated many things, from small black holes and untethered planets to fresh types of particles. But no smoking gun has been found to settle on any one of them.

Astronomers have jokingly named a couple of possibilities: WIMPs (Weakly Interacting Massive Particles) and MACHOs (MASSive Compact Halo Objects, meaning very tiny, dense objects like free-roaming planets or small black holes that are hard to pick out). Many searches for WIMPs are being done in the dark, with experiments deep in old mines or under ice, lakes or seas. For example, the IceCube experiment in Antarctica uses thousands of detectors buried deep in the ice to record flashes of light from particles called neutrinos that interact with normal atoms so rarely they can travel right through the Earth. The jury is still out on their cosmic role.

Another dark conundrum popped up in the late 1990s in surveys of supernovae. Astronomers found that more distant supernovae were dimmer than they were expected to be. After ruling out obscuration by intervening gas or dust, they were forced to conclude that the expansion rate of the Universe is not steady but accelerating: not only is the Universe expanding, but that expansion is getting faster. According to some models, initially gravity may have reined

in the expansion at first, but after a few billion years another force took over and caused the Universe to swell faster.

But the reason for this is still a mystery. The possibility of space inflating more quickly is there in Einstein's general relativity equations – in a parameter called the cosmological constant. Essentially it is a term setting the size of a hypothetical repulsive force that counteracts gravity. Back in the 1910s, Einstein set its value to zero and it was effectively dropped: there was then no need for it, as it made no difference to the calculations. According to Gamow, Einstein referred to including the term at all in his equations as his 'greatest blunder'. But if it is *not* zero then it would affect the expansion rate. This parameter is one way to describe what's going on mathematically. But it is far from understanding it.

With so little to go on, astronomers have reached for another dark term – dark energy – to reflect being themselves in the darkness. They admit that it is just a placeholder for a fuller theory. Nonetheless, they estimate that dark energy would explain the remaining 70 per cent of mass and energy in the Universe.

There are many thoughts about the nature of dark energy, but these are just speculations. It might be linked to releases of energy stored somehow in the vacuum of space. Particles that pop into and out of existence within this sea of energy are predicted by quantum physics, and might cause a kind of negative pressure. But, mathematically, this process is very sensitive to which parameters are chosen: physicists calculating the size of this vacuum energy either find it is so much that it blows up the Universe too quickly for stars and galaxies to form, or it is negligible and has little effect.

Other ideas include the existence of some type of energy field or fluid that acts differently from normal matter. This concept is often dubbed 'quintessence' after the 'fifth element' from which celestial bodies were once thought, by ancient Greek philosophers, to be made. It may also be the result of rips and discontinuities in spacetime. Or current cosmological equations might simply be wrong.

Beyond the reach of their immediate senses, astronomers are left to stumble around this dark side of the cosmos almost entirely within the realm of mathematics. Like a kind of metaphorical cosmic subconscious, dark matter and dark energy control the motions of what we see on the surface. Their origins are deep, yet their nature is mysterious and lies out of plain sight. Astronomers have had to accept that what they thought they knew is not the whole picture. There are far more questions than they have answers to. To find more, they must go back to basic philosophical principles, such as searches for the meaning of life and existence.

Big questions

It's hard to join the dots, to arrange the blur of forces and particles that ultimately underlie the Universe such that they produce an orderly parade of celestial bodies and physical laws. Astrophysicists are left with a slew of questions to address concerning why the Universe is 'just so'.

One conundrum: why is the effect of dark energy so subtle today? Its strength isn't well constrained by any models and it has the potential to be either utterly enormous or infinitesimal or inconsequential. It could easily get out of kilter, inflating voids so fast that the Universe could blister and tear apart. Yet the strength of this anti-gravity term

seems to be finely balanced to avoid this. It tinkers with the motions of galaxies, rather than overtaking them.

Another puzzle is why the Universe is so similar in different directions. For example, the cosmic microwave background is relatively smooth, with temperature fluctuations of just one part in 100,000. Yet 400,000 years ago, when it was emitted, the Universe was big enough that distant parts could not be in direct communication at the speed of light. How has it all come out more or less the same?

And why do light rays travel for vast distances essentially in straight lines, apart from a wobble or two from gravitational lensing? The sizes of warm and cool patches on the microwave sky are just as predicted by Big Bang theory, assuming radiation takes straight routes. They are hardly distorted at all, despite the photons having travelled across the Universe for billions of years.

One solution to these last two problems was proposed in the 1980s by physicist Alan Guth. He posited that the newborn Universe experienced a sudden period of 'inflation', a rapid growth spurt. Thus, the seeds of the hot and cold spots on the microwave sky were imprinted when the Universe was far smaller and all in contact. This inflation also set up the Universe to have just enough density of matter to coast along, expanding gently, rather than suddenly blowing apart or collapsing. It smoothed out any early big wrinkles, like on the surface of a balloon, and kept light moving smoothly.

What caused this inflation is unknown. More than 100 potential theories have been proposed. To examine this nascent stage of the Universe, when it was extremely hot and dense, physicists must appeal to a deeper understanding of the fundamentals of how particles behave

at extremely high energies, well beyond the reach of experiments.

Another core question is why the Universe is made up of normal matter at all, rather than antimatter. Particles with the opposite charge and physical traits to conventional particles – such as positively-charged positrons (or anti-electrons) – were predicted in 1928 by British physicist Paul Dirac and discovered soon after. But most stuff is made of normal matter. In the early Universe, something must have happened to tip the balance. One answer might lie in slight differences in the speed of decay of particles and their antiparticles. Perhaps, as space expanded, more matter particles survived.

The laws of physics take us a long way back, but only so far – to one millionth of a second after the Big Bang. Earlier than that, and everything's unknown, and though that might seem like a tiny period, it's a crucial one. Ultimately a new theory of 'quantum gravity' may be needed to bring everything together, by unifying quantum behaviour at subatomic scales with gravitational forces and spacetime.

Another issue such explanations must contend with is how chance seems to play an outsized role in how our Universe has ended up. Lots of aspects are statistically unlikely – from the particular strengths and scales of various physical forces to the many steps of chemistry that led to life on Earth.

For example, why is the Universe we live in so perfectly conducive to allowing humans to exist? This issue is also known as the 'anthropic principle'. If gravity was slightly stronger or dark energy a little more powerful, then stars and galaxies might not have formed, let alone planets around them with oxygen-rich atmospheres and complex carbon chemistry capable of producing us. On the one hand, if any of these things was different we wouldn't be here. But

on the other, why should all these things be so precisely balanced? It's the sort of question that has kept philosophers awake at night over the centuries.

One avenue being explored as a way to answer some of these 'just so' questions is the possibility, at least on paper, that our Universe is just one of many. Within this 'multiverse', anything is possible, at least somewhere. No matter how improbable, we live in the part that suits us best.

The idea of multiple universes, each with slightly differing properties, dates back to antiquity. For example, ancient Greek philosophers including Pythagoras in the 6th century BCE conceived of a co-existing series of 'kosmoi' – different orders or arrangements or harmonies ('kosmos') of atoms, whirling together to form planets and stars.

The word 'multiverse' was coined by philosopher William James in his 1895 book *Is Life Worth Living?*, albeit in the different context of 'a moral multiverse'. Scientists came closer to its current usage in the nineteenth century. In 1895, for example, German physicist Ludwig Boltzmann envisaged how different parts of the Universe might have different thermal properties, although these regions were still within one whole.

In 1957, US physicist Hugh Everett published the 'many worlds' concept, inaugurating our modern understanding of the multiverse. This proposes that parallel universes split off each time an event happens at the quantum scale, at least mathematically speaking. This idea quickly captured the public imagination. In 1965, British science-fiction author Michael Moorcock used the multiverse as a plot device in his novel *The Sundered Worlds*. Since then, it's become a widely used fictional trope to explore the far-reaching

consequences of making different choices in life, as in the 1998 film *Sliding Doors*.

Researchers differ in how far they believe in the reality of the multiverse. Some see it as just a mathematical construction, a way to work out the probabilities and avoid existential angst. Others take it to reflect an aspect of reality, linked in ways we don't yet know to the physical cosmos of particles and energy.

There are alternative theories, including 'string theory', which describes particles as one-dimensional objects that behave like tiny loops of string in other dimensions. These loops vibrate with characteristic harmonics, giving them their physical and quantum properties. There are many variants of string theories, but these and others can be used to hypothesise about the origins and nature of the Universe in ways that go far beyond observations.

How, for example, did the Universe form? Might it have flared up at random from a flash of energy or clashes between different dimensions of space-time? Might it not have been one single event but an ongoing series of outbursts – a 'big bounce'?

But no matter how much we can deduce or contemplate, there's always a further step we cannot fathom. For example, if the Universe – or multiverse – was set off by some quantum energy burst that produced a particle that begot more particles, who or what set the rules in motion in the first place? Quantum physics experiments show, for example, that whether a particle behaves like a discrete object or as a wave depends on how one chooses in advance to measure it. The 'observer' plays a role in the experiment. Everything is connected.

Italian writer Italo Calvino poked fun at this in his marvellous book *Cosmicomics*, published in 1965. In this

collection of a dozen short stories, an eternal being called Qfwfq shares tales around events in the history of the Universe. In one tale, Qfwfq spots a sign hanging from a distant galaxy. It says: 'I saw you.' After working out that the light from the galaxy was issued two hundred million years before, the being thinks back to what he was doing at that time, and feels ashamed: 'I was seized by a ghastly presentiment.' How did anyone in a distant galaxy know, he wonders?

Qfwfq considers what to do about it, whether to post a sign back perhaps saying 'what of it?' But then his mind starts whirring. How far might the message have spread in those millions of years? 'It was as if in the space containing all the galaxies the images of what I had done that day were being projected in the interior of a sphere that swelled constantly, at the speed of light.' All he can hope for is that the galaxies recede from him so fast that they disappear out of sight, forever.

All these questions leave me, and most astronomers, as befuddled as Qfwfq. Many physicists are content to take the mathematics and physical laws written down as equations as a fair equivalent to the real cosmos, as telling us how it works and perhaps why certain things occur. But, to me at least, it leaves a gap, a bit like a recipe in a book doesn't quite live up to the final meal.

Cosmic endings

To end then, let's consider what the fate of the Universe might be. Will it keep swelling forever or fall back in on itself in a 'big crunch'? Might it undergo boom and bust cycles? The answer depends on the balance of various forces as well as matter and energy. And, to some degree,

how we think about it depends also on our own experiences of time.

According to Big Bang theory, we are halfway through that movie now. More than a century of observations of stars and galaxies and the cosmic microwave background tell us that the Universe is around 14 billion years old and should last at least as long again. That sounds like a big number, and a big margin of safety – nothing to worry about any time soon. But recent discoveries have added uncertainty to that picture. Not much is likely to happen immediately, or for billions of years, but it's fair to say that the story of the Universe, as far as we can read its plot line, has an open ending. And perhaps that makes it even more compelling to read.

Back in the 1990s, before dark energy was discovered, most astronomers thought that they had the measure of the Universe's future, to some degree. The mass and rate of expansion of the cosmos seemed to put it on a slow glide path, expanding forever, perhaps slowing but probably never actually reaching a stop. But then the detection of dark energy puts that all up in the air. Just as the origin of the cosmos is unfathomable, so is its fate.

The unknown nature of dark energy adds a question mark. We simply have no idea how this anti-gravity force will behave. If the expansion of galaxies away from one another continues to accelerate, they might all disappear from our view, to leave us alone in our city of stars, the Milky Way. Roll the film forwards, and eventually even galaxies might be pulled apart, into their constituent stars. And those stars, too, might one day evaporate into a mist of atoms pervading all of space.

But might some other fundamental force pop up to change this bleak picture, to slow or reverse the expansion,

for some as yet unknown reason? Might the Universe find a way to contract in far off years, to collapse, and perhaps initiate a fresh Big Bang? We know too little about the dark side of the Universe to say for sure.

It's interesting to ask, though, why we even consider these questions. Why should the Universe have a life story and fate, like we do? Central to our interpretations of the cosmos is our own sense of time. Scientists and most people today think of time as a linear 'arrow', extending from the past through the present into the future. For example, once we can define a month or year based on the position of the Moon or Sun, we can start to speak about what we will do in five years' time or how long it has been since we were born. But inherently, this timescale is set by the motion of our satellite around our planet, or our planet around its host star. It's a timeframe that relates to humans, and which we can relate to.

Does it make sense to speak of the Universe in the same way? Just as we age, we imagine the Universe ageing, becoming more complex and sophisticated as it matures, like a bottle of fine wine. We tell a cosmic narrative of progress: planets form from messy gas clouds, galaxies cohere, black holes grow fatter, life develops, intelligent life appears. Everything is set up from the start to produce us, in other words.

But, again, the underlying cold, hard logic of physics tells a different story. Physicists often explain the arrow of time as a result of everything becoming increasingly disordered, as heat from the Big Bang diffuses. Time is more of a winding down process, as the Universe descends into ever more chaos. This is based on the second law of thermodynamics, as put by Rudolf Clausius in 1850, which states that 'the entropy of the world tends towards a

maximum'. Entropy is a measure of disorder – for example when an ice cube melts to form a puddle of water, its molecules become more disordered.

The second law of thermodynamics was also widely taken to imply that the Universe had a finite age – and thus a beginning. If the Universe was infinite, then it would already have mostly run down. The chance of us existing in the ordered world that we see around us was vanishingly small in an everlasting Universe. The fact that radioactive minerals existed, with atoms within them decaying into other elements and releasing forms of radiation and particles, also suggested that they had not been around forever.

Clausius went on to argue that this one-directional process meant that a cyclical Universe was impossible. And he coined the term 'heat death' for the final state: when entropy reaches a maximum, 'no further change could evermore take place'. A Universe ending in a mist of subatomic particles would pretty much fit this bill.

But other physicists of the time were uncomfortable with this bleak vision. What's the point of the Universe if it only leads to a dead end? Clausius's critics argued that the second law might not apply to the distant past or future of the Universe. Or perhaps the maximum entropy was never reached, as it took eternity to reach it. There might be pockets of the Universe where entropy had not wound down as fast as in others – heat death might be patchy. Might some regions cling on, despite cosmologists treating everywhere as the same though their equations?

Such loopholes left more space for hope. While many human cultures have contemplated the 'end of the world', most cling to the aspiration that some aspects of humans will somehow survive, be it their souls, offspring or works.

Concepts of cyclical time, and endless series of recurring events, are common in cultures around the world.

For example, the Mayans used a series of calendars of different lengths, including one of 260 days (or roughly the length of a human pregnancy), one around one year long, and another spanning approximately 400 years for recording longer term events. Philosophers in ancient India imagined even longer cycles – extending for billions of years, or truly cosmic timescales. A divine year (or mahayuga) lasted 12,000 years; 360 of these cycles make up a cosmic cycle, or 4,320,000 years. One thousand mahayugas makes up a day in the life of the god Brahma, who lives for a hundred years' worth of these days. After his death the cycle repeats. Cyclical time is also linked to ideas of reincarnation. Buddhists meditate aiming to transcend time and make its passage stop.

We all hold on to some cyclical aspects of time. Our body clocks are attuned to day-night and monthly cycles and the seasons on our planet provide a steady background tick. Anniversaries are recurrent. Each year – as we make one turn around the Sun – we loop back to the moment we were born, married or lost someone dear. Calendars and almanacs were developed to ensure people pray or celebrate at the right time, be it each year or when the stars and planets align. Dates of battles, acts and treaties are revisited centuries later. There is no meaning in the number of years we choose to mark. Humans have ten fingers and like multiples. 'Only an anniversary gives a community certainty that achievements can defy mortality,' art historian E.H. Gombrich wrote.

Linear time is a better bet, though, when we want to tell a story – whether about us or about the cosmos. And any narrative needs a starting point. For example, religious tales

of the creation of the Universe, such as that captured in the Bible, spread around the world through Judaism, Christianity and Islam. Geologists worked out the age and origin of the Earth in the nineteenth century from fossils and radioactive minerals. The theory of evolution is also one way.

Yet, modern physics also offers more complex views of time than Clausius could have foreseen, or than any practical society would base itself on. Einstein's theories of special and general relativity proposed there was no such thing as absolute time in the Universe. Because space and time are connected, and the speed of light is fixed, people would experience time differently in different parts of the Universe or even when travelling at different speeds. Spacetime would warp, such that time runs more slowly the faster you travel.

To illustrate, Einstein described the 'twin paradox', where one twin remains on Earth and the other flies to the Moon and back. According to Einstein's theory, time passes more slowly for the spacefarer, so the twins have different ages when the traveller returns, such that the astronaut is younger. The same effect has been measured by comparing an accurate clock that's flown in a plane to one that's remained stationary on the ground, although in practice for journeys like these the time difference is scant.

What this means for our understanding of the cosmos as a whole is easier said in equations than words. Essentially, everything is connected; space and time are enmeshed, like warp and weft in a woven cloth. Perhaps there's no cosmic life story, just a shifting form of existence.

Artists have also looked for ways to comprehend this new way of looking at the world. Einstein's four dimensions of space and time might have influenced the Cubists, including Pablo Picasso and Georges Braque, leading them to

fragment traditional perspectives and show different facets of objects next to one another in distorted views. Italian painter Giorgio de Chirico painted architectural canvases full of clocks and starkly sunlit railway stations, mirroring some of Einstein's inspirations for his theories from relative motions experienced on trains. In a 1931 painting called *The Persistence of Memory*, Spanish Surrealist Salvador Dalí's melting pocket watches, draped over a branch and wall, have been described as symbolising the dissolution of ideas of cosmic order.

A century on from Einstein's spacetime revolution and Hubble's discoveries, we are still swimming in their currents. The intricacies of the Universe's mechanisms only look more mysterious the more we learn about them. The maths works. Technologies have moved on. But have our heads and hearts? Are we content to accept that the world around us is full of quantum particles popping in and out of existence, black holes, galaxies stretching ever apart – is there romance and a sense of belonging in that? Or are we still tied to the Moon, planets and stars in all the emotional, visceral and intuitive human ways that we've always been?

Ever larger telescopes pick out ever fainter details of distant galaxies. But the more we find out, the more they bring us back to our own Milky Way, arching resplendently above us in the night sky. The more we search for planets around other stars, the more we appreciate and yearn for the landscapes of those near and including our own. Black holes, dark matter and dark energy are the twenty-first century equivalents of shadows cast on the surface of the Moon, begging us to learn more about their inkiness.

What new answers will this century hold? I don't know. But I do know that we'll never stop trying to comprehend the

cosmos we are part of. And seeing it reflect ourselves everywhere we look.

Epilogue

Each year, at least two total solar eclipses are visible from somewhere on Earth. They are usually remote, seen only from places like the middle of the Indian Ocean or the Faroe Islands. Most people will only see one or two in their lifetime.

The first total eclipse I witnessed was in the southwest of England in 1999. Unfortunately, it was blanketed by thin grey cloud. But while this meant we didn't witness the eclipse's full glory, we could see the gradual eating away of the Sun's disk by the Moon as the eclipse began. Standing high on a hill looking out across the English Channel, I remember seeing the dark wings of the eclipse's shadow of totality race towards us over the water, like an approaching thunderstorm. For a minute we were swathed in darkness. Then the shadow moved on, hurrying up the coast.

Hoping to better this, in August 2017 I travelled to Idaho in northwest America to see another. This time I was not disappointed.

It started imperceptibly. Around midday, my friends and I raced to the top of a scrubby hill and set out blankets and backpacks. The sky was cobalt blue and clear, a low haze of smoke from distant forest fires smudging the horizon. We sat down amongst herb-scented mounds of sagebrush shivering with chirping crickets. Everything seemed normal, until we raised our eclipse glasses to shade our eyes. There

it was – a pit in the Sun's cheek. Unmistakeable. It had begun. The eclipse was happening, right on cue.

It is a slow process, this turning of cogs in the cosmic clockwork. Our gazes wandered across the notched mountains beyond. Idaho's Sawtooth range is well-named. We chattered and joked, poured wine into paper cups. But over ten minutes, twenty, the power of this event steadily and quietly took a grip. The chatter faded. Each of us began to withdraw and find our own space, tuning in to our senses.

The quality of daylight began to shift. Colours muted, making the landscape look like a faded 1970s postcard. The Sun's heat began to wane and icy blasts of wind brushed our bare arms. To our delight, shadows began to curve and blur. We projected miniature crescents through gaps in our fingers onto paper.

Luckily for us, we had space to take it all in. We were remote from the millions of other watchers cramming freeways and parking lots in a congested line across America's flanks. The path of total darkness spanned the continent, first blackening Oregon's Pacific shores before heading east to the Atlantic coast of South Carolina. News anchors and even jet fighters chased the Sun and Moon across the US.

Looking up again, another swathe had gone. There is no way to speed the process up, and no stopping nature's clock. As the minutes ebbed, the bitten orb became a crescent. A horned devil in the sky.

It was much darker now, as if a vast cloud had invaded, a storm was brewing. Cosmic forces of gravity kept swinging the Moon into the Sun's path. The crescent shrank to a slither. Daylight extinguished.

And there it was! The last orange segment of the Sun coalesced into a bright drop, becoming the 'diamond' set in

a ring of fire. Suddenly the Sun and Moon were embracing, locked together. Silver arms reached out from the ring's black heart - jets of scorching gases flung off the solar surface. We could see planets and bright stars in the indigo sky and the crisp purple silhouettes of the mountains. Two minutes later, the solar apparition burnt out and the Sun reasserted itself. A second dawn arrived that day.

Watching the eclipse made me feel small - a puny human standing within a vast landscape on this complex and wondrous planet. There is something primitive about watching the Sun being consumed. Day becomes night and returns within minutes. Light levels and shades of landscape constantly shift. It's dramatic, unforgettable.

But, to my surprise, I didn't feel scared, worried or alone. Yes, I was connected to all the other people watching this spectacle, my friends and others gazing up from car hoods and lawn chairs. But I also felt close to all those who have ever contemplated such events over the ages - the eclipse-chasers, astrologers, generals, kings and college kids. I was humbled by nature's monstrous machinery, its vast wheels turning day and night, year after year, century after century. But I felt unexpectedly calm and centred. It was strangely comforting - not scary - to feel part of it all, temporarily in the cosmic spotlight. It changed me a little; I felt more secure somehow.

As I wrote this book, that sense of continuity stayed with me. I am proud to have played a little part in humanity's great cosmic quest, at least in the background chorus. I still marvel at all that's out there. But I also worry about what we are doing in space physically today, using it just as a playground, or worse a war zone, ripping it off, ignoring its cultural significance for everyone on Earth.

Outer space is still very much seen as the preserve of the expert, the powerful and the rich. Only elites that can afford to build powerful rockets and billion-dollar telescopes with which to see and map the Universe are enabled to know its secrets, and with them to co-opt its immense power. That's been true for as long as humans have looked to the skies, and it remains true today.

And, while some cultures still have a close relationship with the skies and feel an intimate connection to what goes on there, the majority of people, especially city-dwellers, increasingly see space as remote and irrelevant to their lives. It is viewed as a technical domain, an outpost run by and for others. It's left largely unregulated as a result, a place where almost anything goes.

Yet history shows that humanity doesn't have a good track record in similar circumstances. Waves of science-fiction writers have projected the risks of transcending earthly boundaries without limits. But we still seem to want to emulate those plots – and relive eras of rampant colonialism, competition and inequity, as long as we're the winners – rather than heed the warnings or learn from them.

While the 1966 United Nations Outer Space Treaty still aims to preserve space as a 'province for all mankind' and for 'peaceful purposes' only, with astronauts as our 'envoys', reality is far looser. Such ideals don't stop us from filling orbits around Earth with debris from expired satellites and hundreds more fresh ones lofted eagerly each year. In future skies, some meteor showers might signal clouds of space junk burning up as they fall to Earth, rather than natural sights. The dated language of the treaty and lack of enforcement leaves room for widening some military uses of space – and potentially for real star wars.

There are hopeful signs, too, though. Astronomers and others are championing dark skies and setting up nature reserves away from the polluting glow of streetlights, recognising that the sky is just as much part of the environment as the land below it. Researchers have been up in arms about the rapidly increasing numbers of satellites in our skies, which make it harder to peer into the Universe without bright flashes staining the view. Maybe astronomers have more in common with the poets who critiqued the Apollo programme than they thought. Indigenous peoples are speaking up, too, about the cultural significance of the Moon and sites with cosmic significance on Earth. But why stop there?

Space is much more than a source of resources to be plundered or a branch of physics. It's part of humanity, and vice versa. Our stories are etched on the skies. We are all starwatchers – the night sky is a constant in our lives and throughout human history and culture. Whenever I am lucky enough to look through a telescope and notice how Saturn's rings change aspect or Jupiter's moons shift back and forth over time, I am reminded how they, too, are part of our twenty-first century, shifting and changing, experiencing their own weather and storms, as we are on Earth. We share this Universe: these places are not just fixed images in books or on screens, they are real and ever-changing as the cogs of the cosmos turn, ageing as we age.

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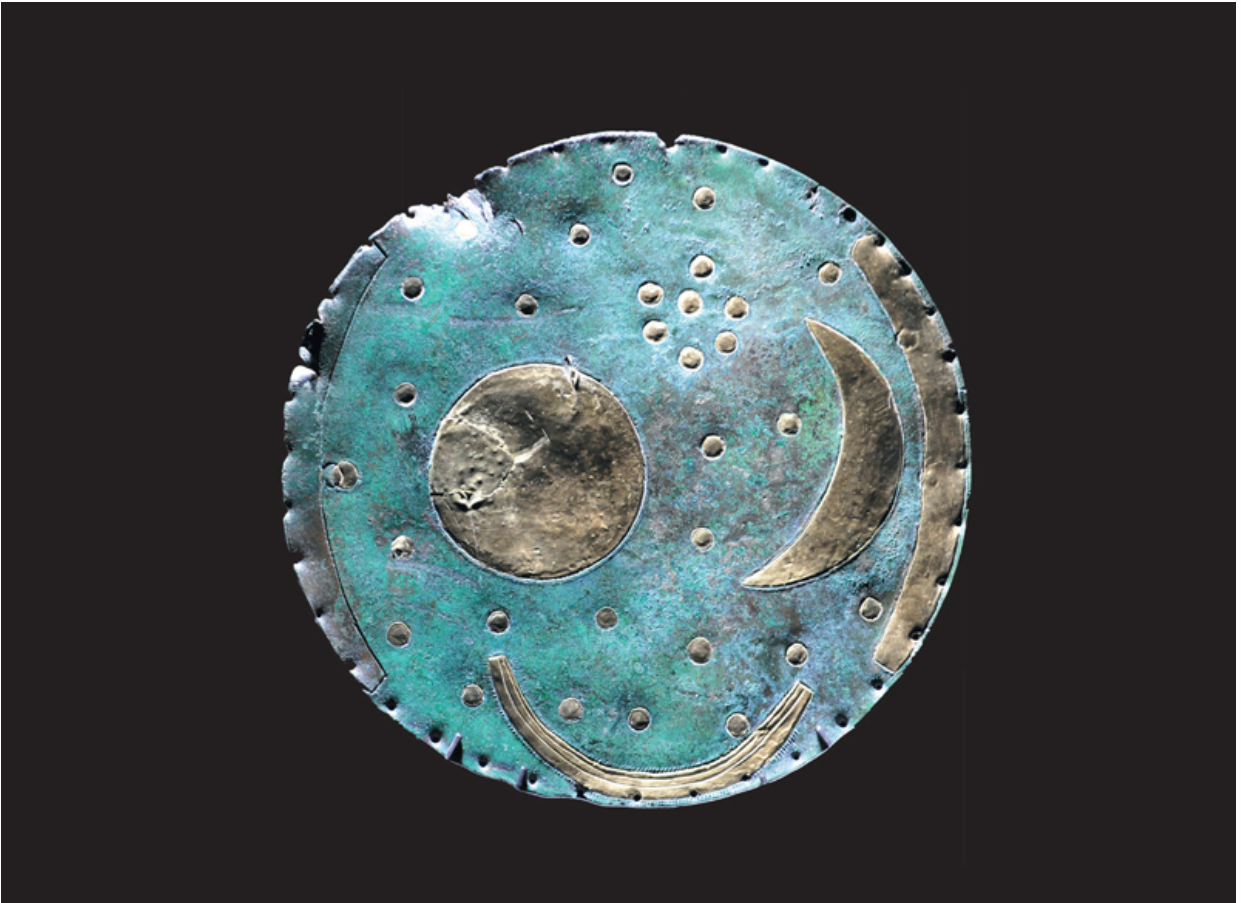
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A Note on the Author

Joanne Baker is a writer and editor. She holds a PhD in astrophysics from the University of Sydney and master's degrees in natural sciences and landscape architecture from the Universities of Cambridge and Greenwich. Baker has a background in astronomy research, where she studied quasars, black holes, galaxy evolution and cosmology. She has been a NASA Hubble Fellow at the University of California, a Royal Society University Research Fellow at the University of Oxford and a Radcliffe Fellow at Harvard University. She has written three books on physics and edited for *Nature* and *Science magazines*.

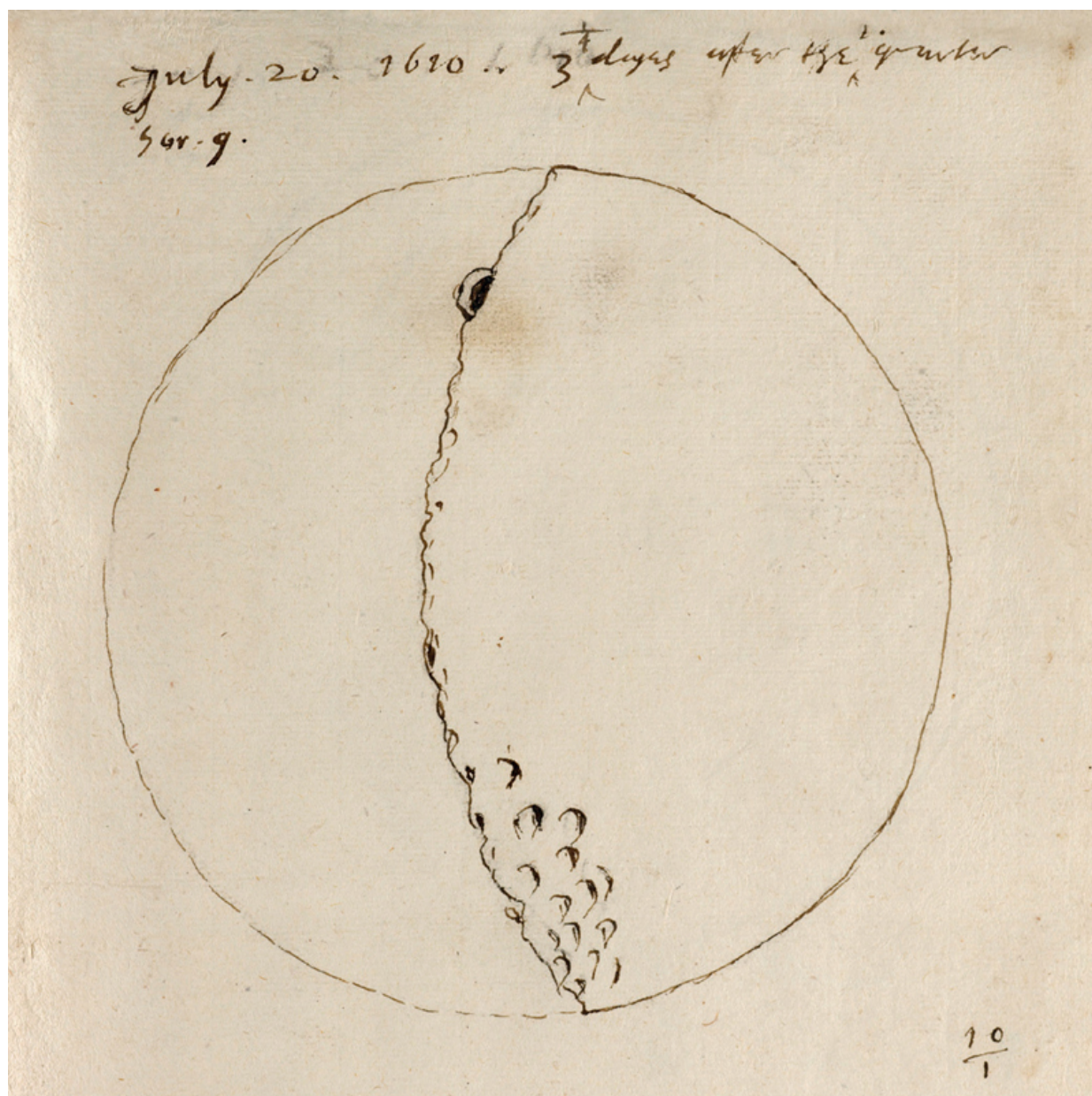
Plates Section



The 3,600-year-old Nebra sky disc, found in Germany, includes gold symbols representing the Sun, Moon and stars.



Babylonian priestess Enheduanna depicted on a white calcite disc, c. 2400 BCE.



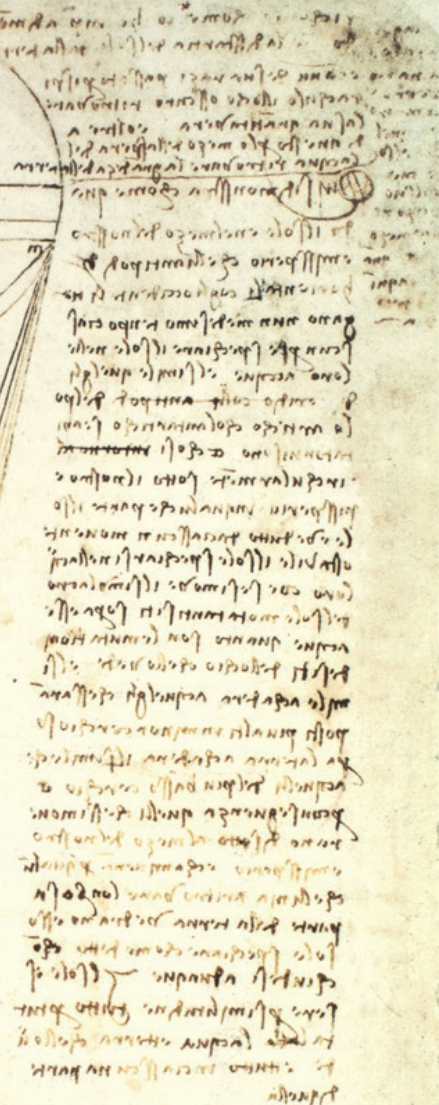
Thomas Harriot's sketch of his telescopic observation of the Moon, 20 July 1610. Harriot made the first known recorded telescopic observations of the Moon on 26 July 1609, preceding Galileo's by several months.

廣寒宮闕舊遊時
鶴天香捲綠旌自是
嫦娥愛才子桂宮折
與最高枝唐寅

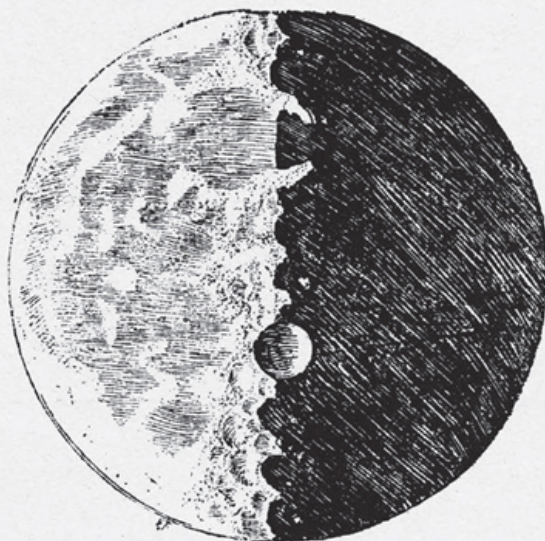
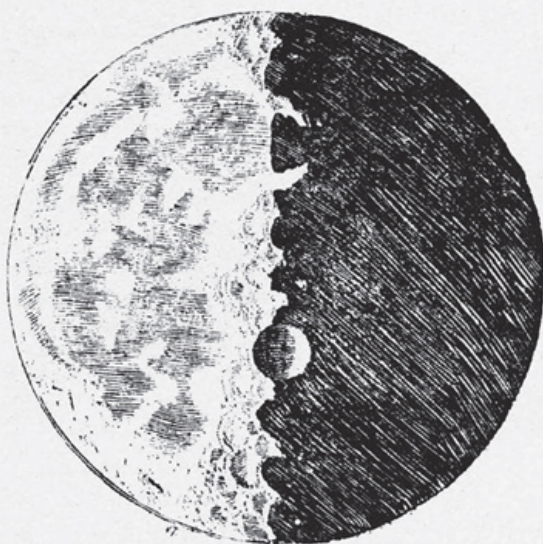
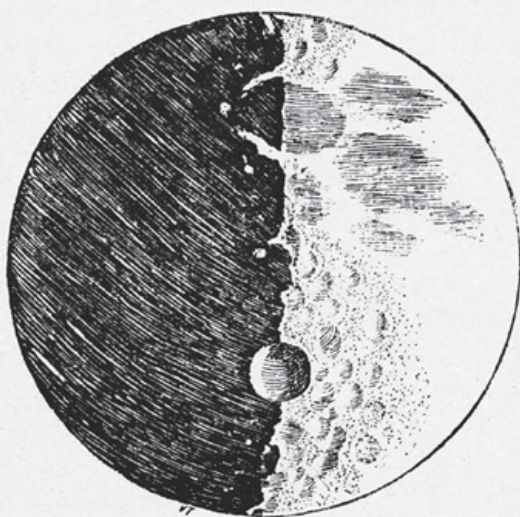
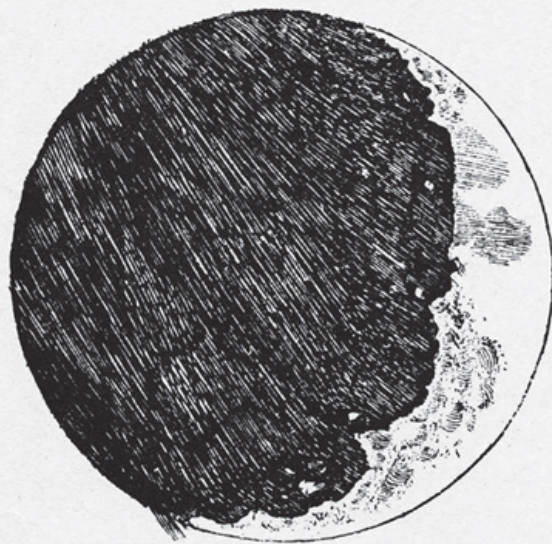


An ink and colour depiction of the Moon goddess Chang'e, from the Ming dynasty (1368-1644), China.

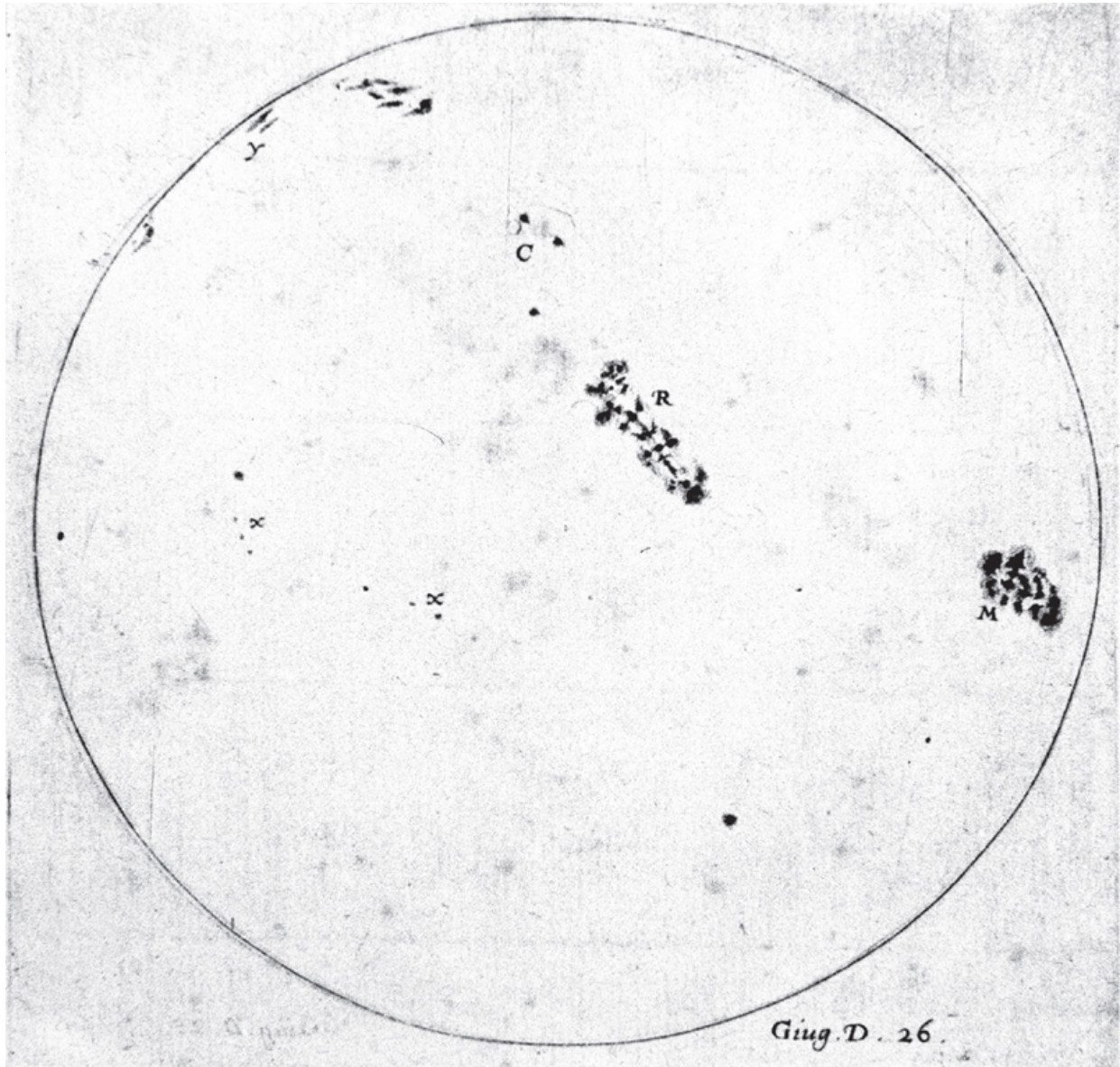
The diagram depicts a circle with a vertical diameter. To the right of the circle is a vertical line segment with several points marked. From each of these points, a line is drawn that converges towards a single point on the far right. This setup likely represents an optical experiment or a geometric proof related to the properties of light or lenses.



Leonardo da Vinci studied the illumination of the Moon in his treatise *Codex Leicester*, c. 1510.



Galileo made detailed sketches of the Moon as seen through a telescope, included in *Sidereus Nuncius*, 1610.



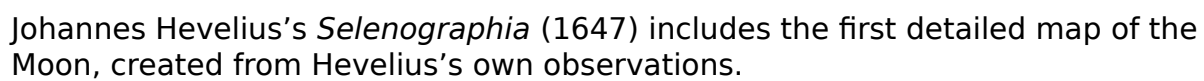
Galileo recorded sunspots, by projecting light from the Sun, 1613.



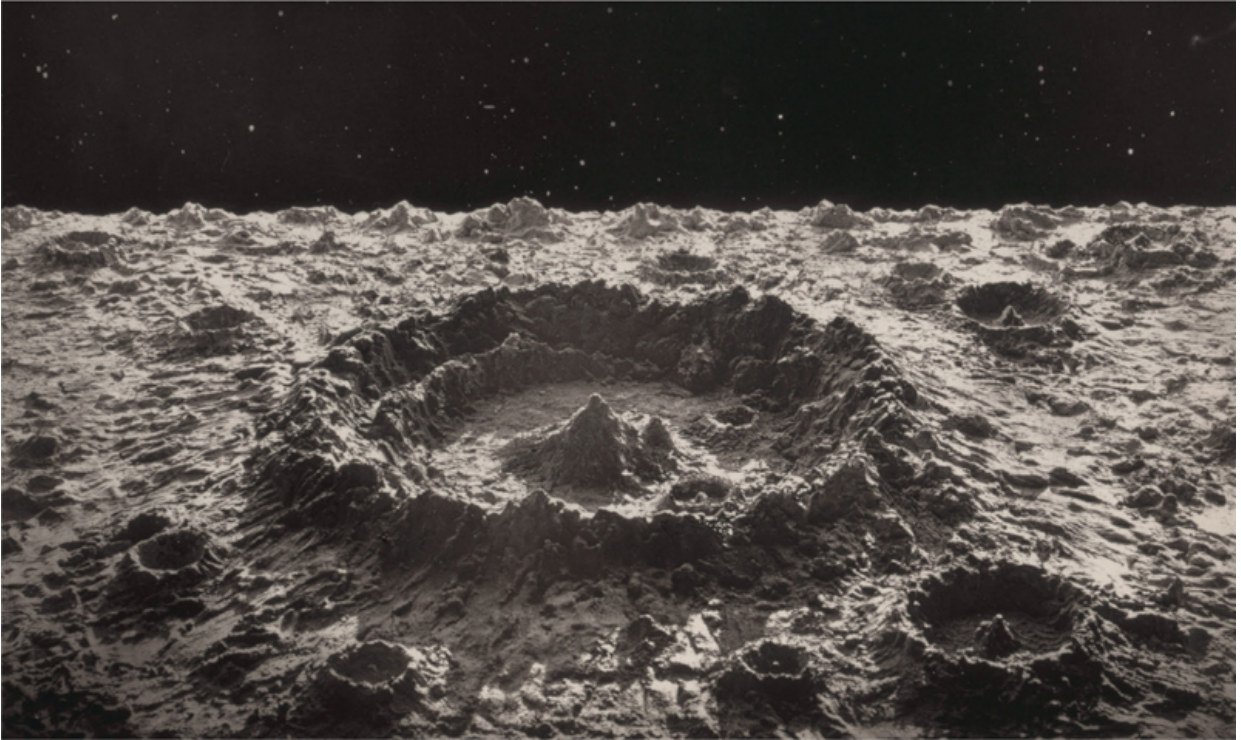
The Moon's links to women and 'lunacy' are nodded to in this satirical engraving from 1652.



An early photograph of the Moon taken through the telescope at the Harvard College Observatory by John Adams Whipple, 1857-60.



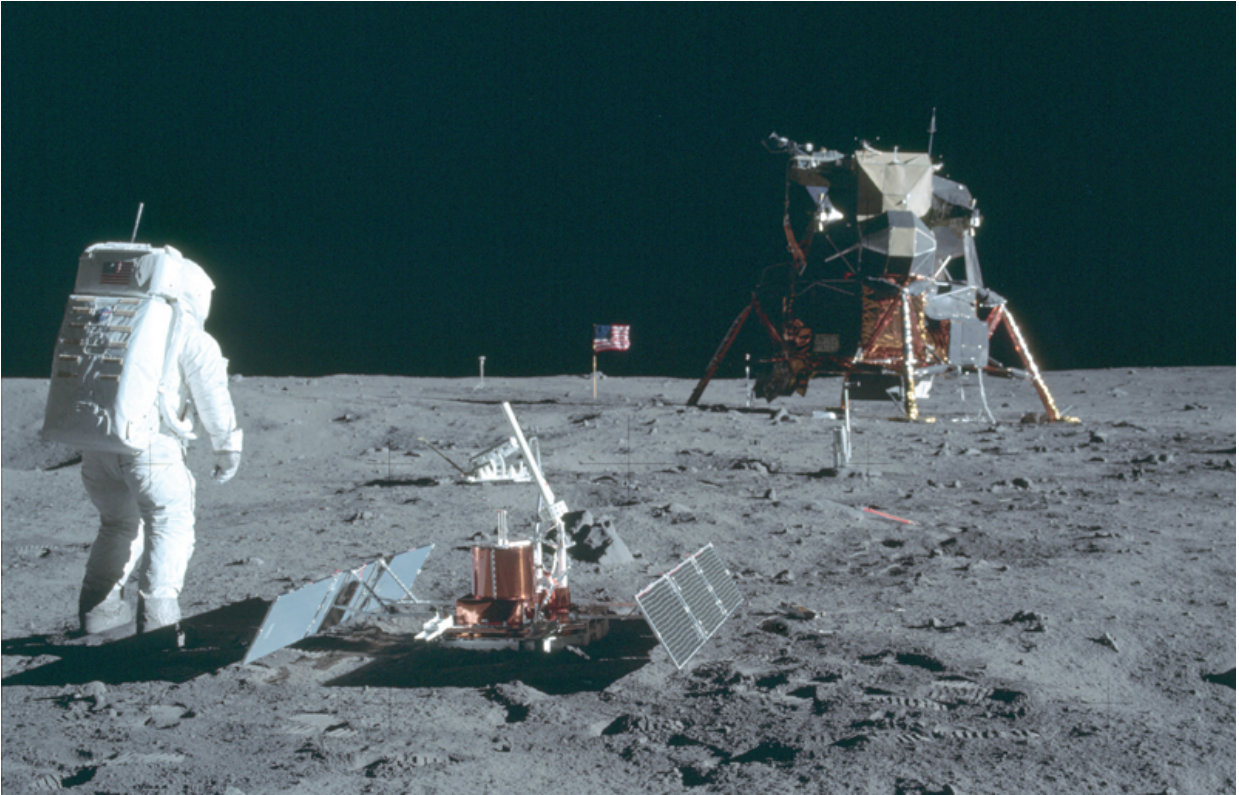
Johannes Hevelius's *Selenographia* (1647) includes the first detailed map of the Moon, created from Hevelius's own observations.



James Nasmyth's photograph of a plaster model of a lunar crater, c. 1874.



The first boots on the surface of the Moon, as photographed by the Apollo 11 astronauts, 1969.



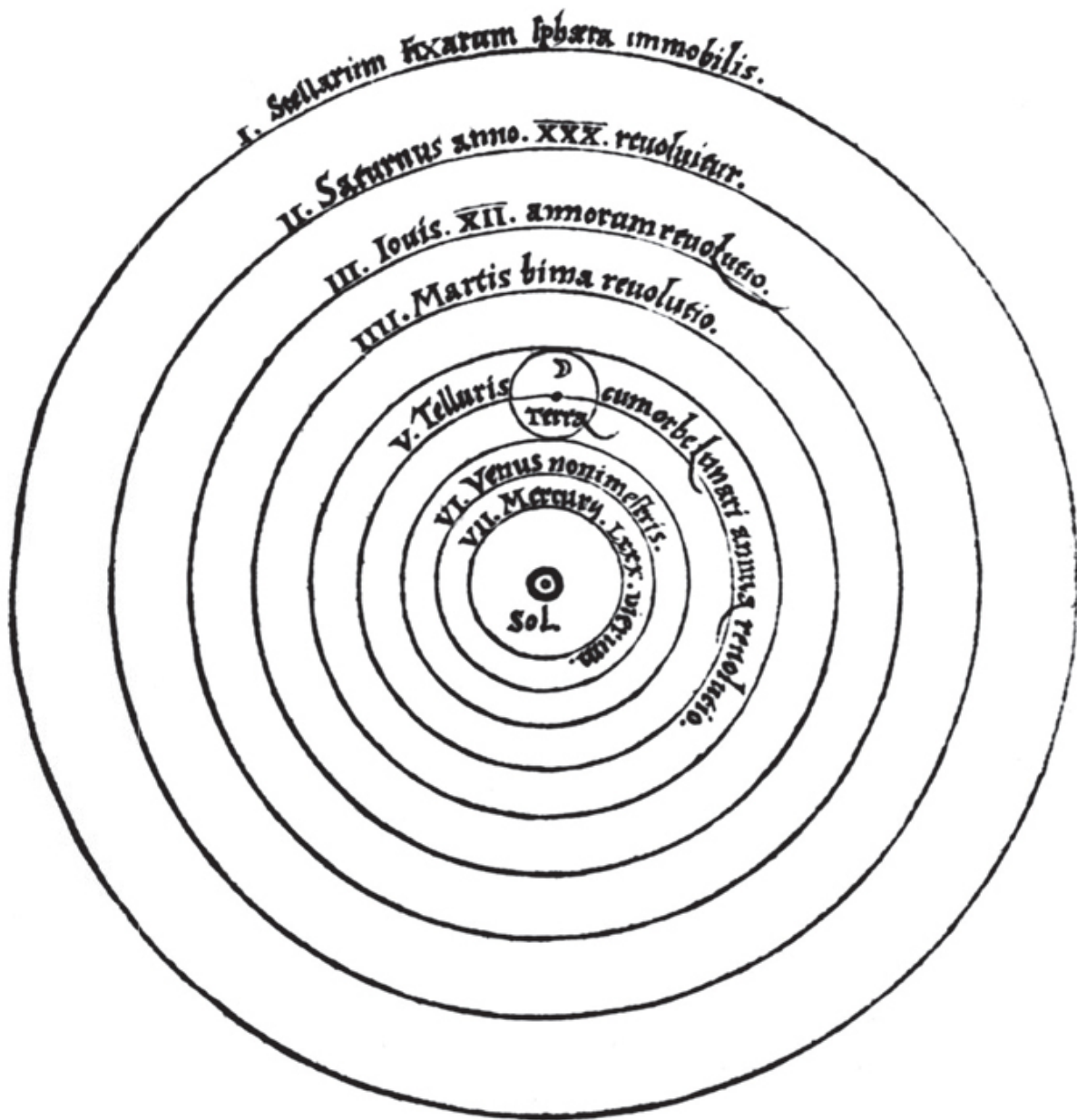
The Apollo 11 lunar lander, 1969.



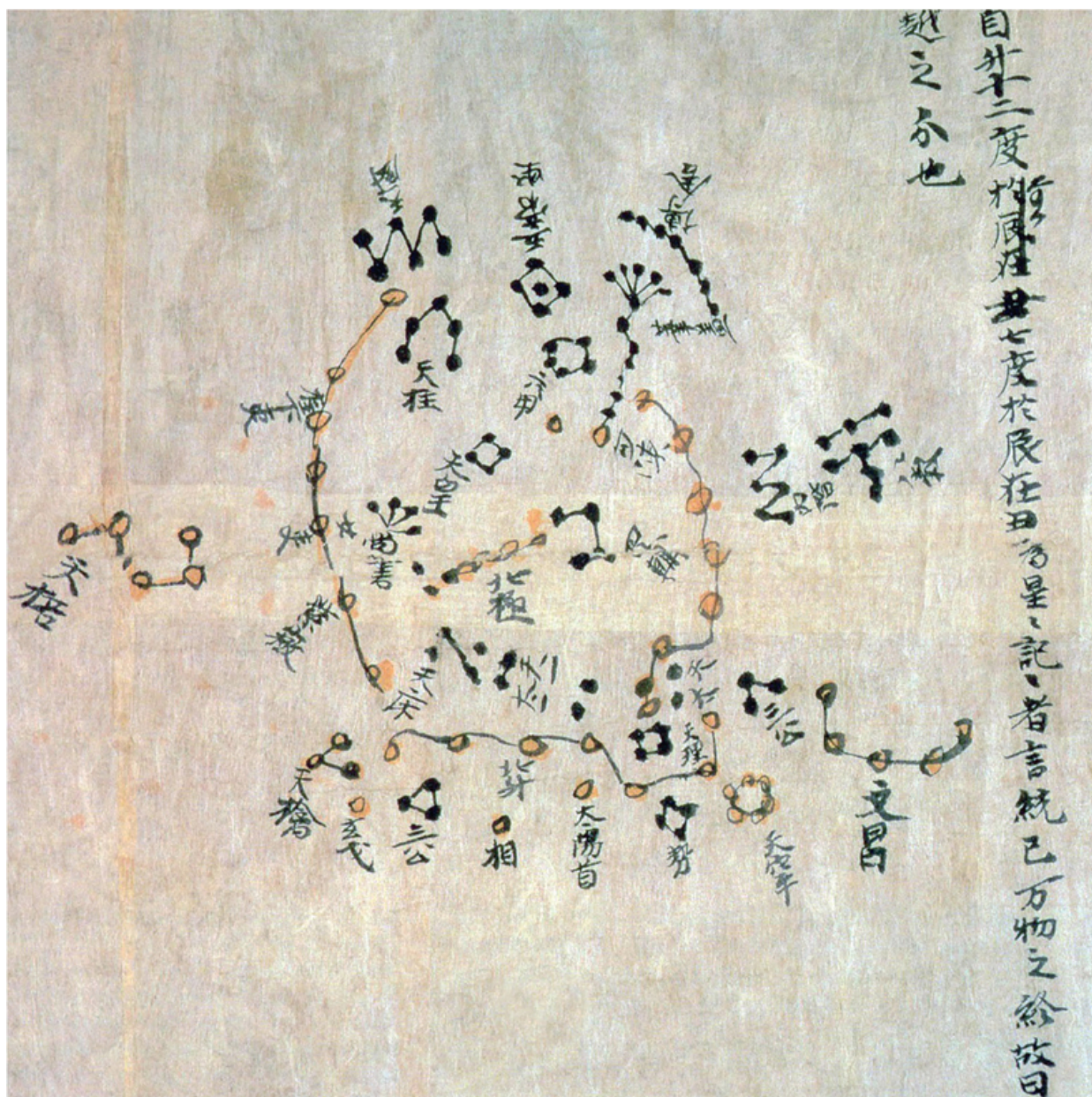
Earth rising over the Moon, as snapped during the Apollo 8 flyby, 1968.



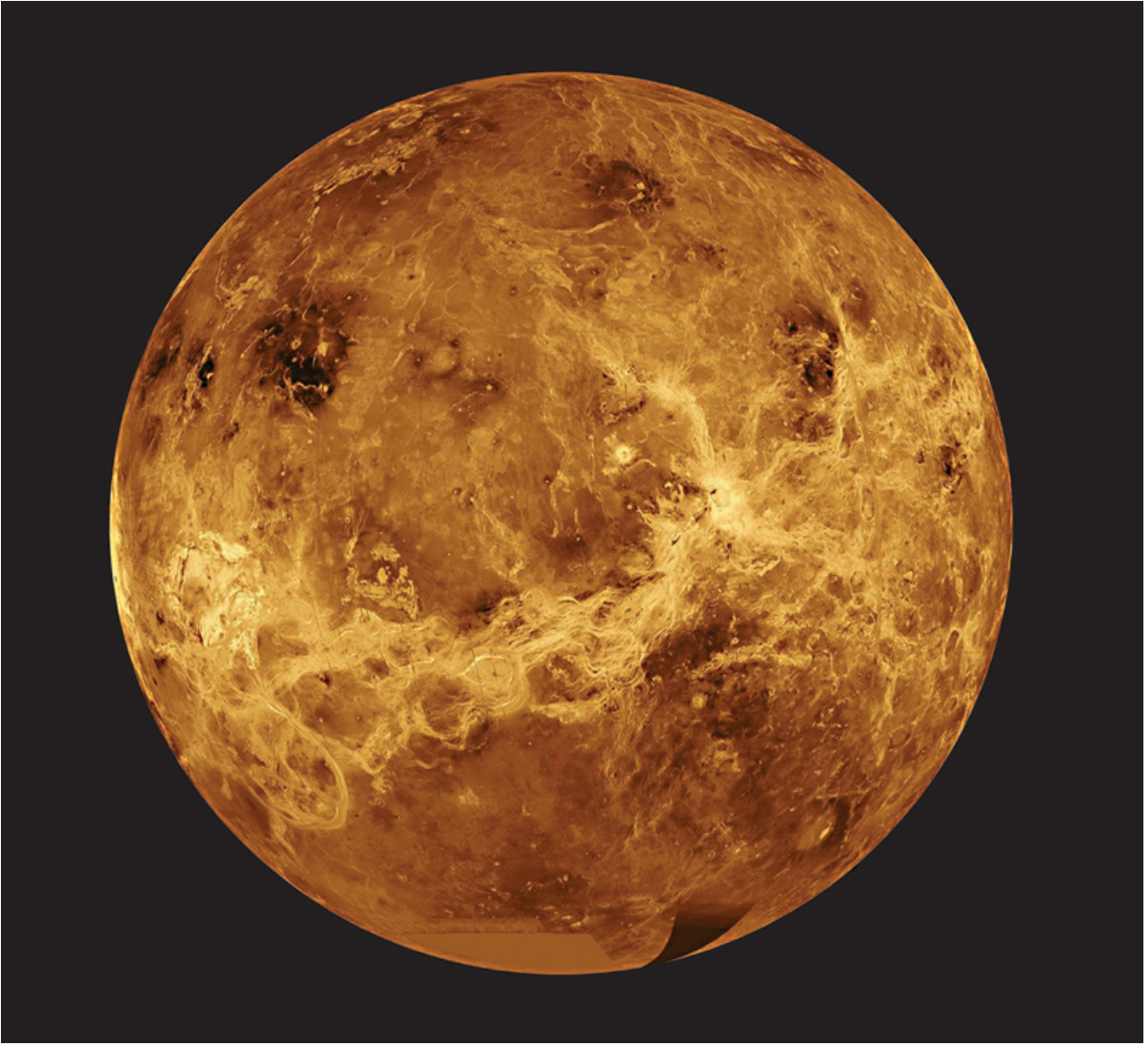
Babylonians recorded astronomical events daily in cuneiform script on clay tablets for more than 600 years.



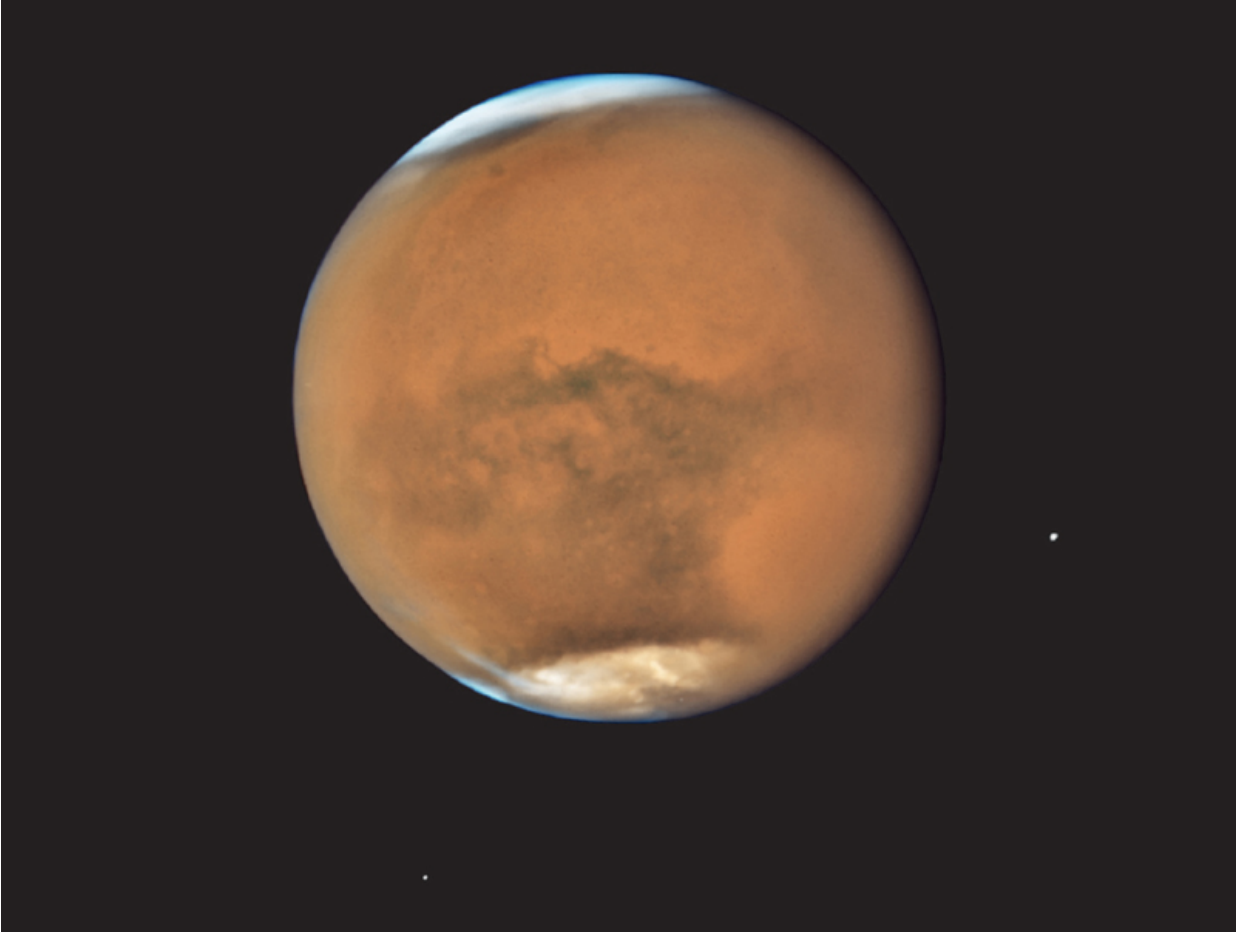
Copernicus showed that the Sun, not Earth, lies at the centre of the solar system in his 1543 treatise *De Revolutionibus*.



A fragment of the Dunhuang star atlas, showing stars around the north celestial pole, China, c. 700 CE.



Venus has a scorching hot rocky surface lying beneath its hazy atmosphere, as measured by NASA's Magellan spacecraft in the 1990s.



A huge sandstorm on the surface of Mars, photographed by NASA's Hubble Space Telescope on 18 July 2018.



The surface of Mars as seen by NASA's Perseverance rover in 2023.



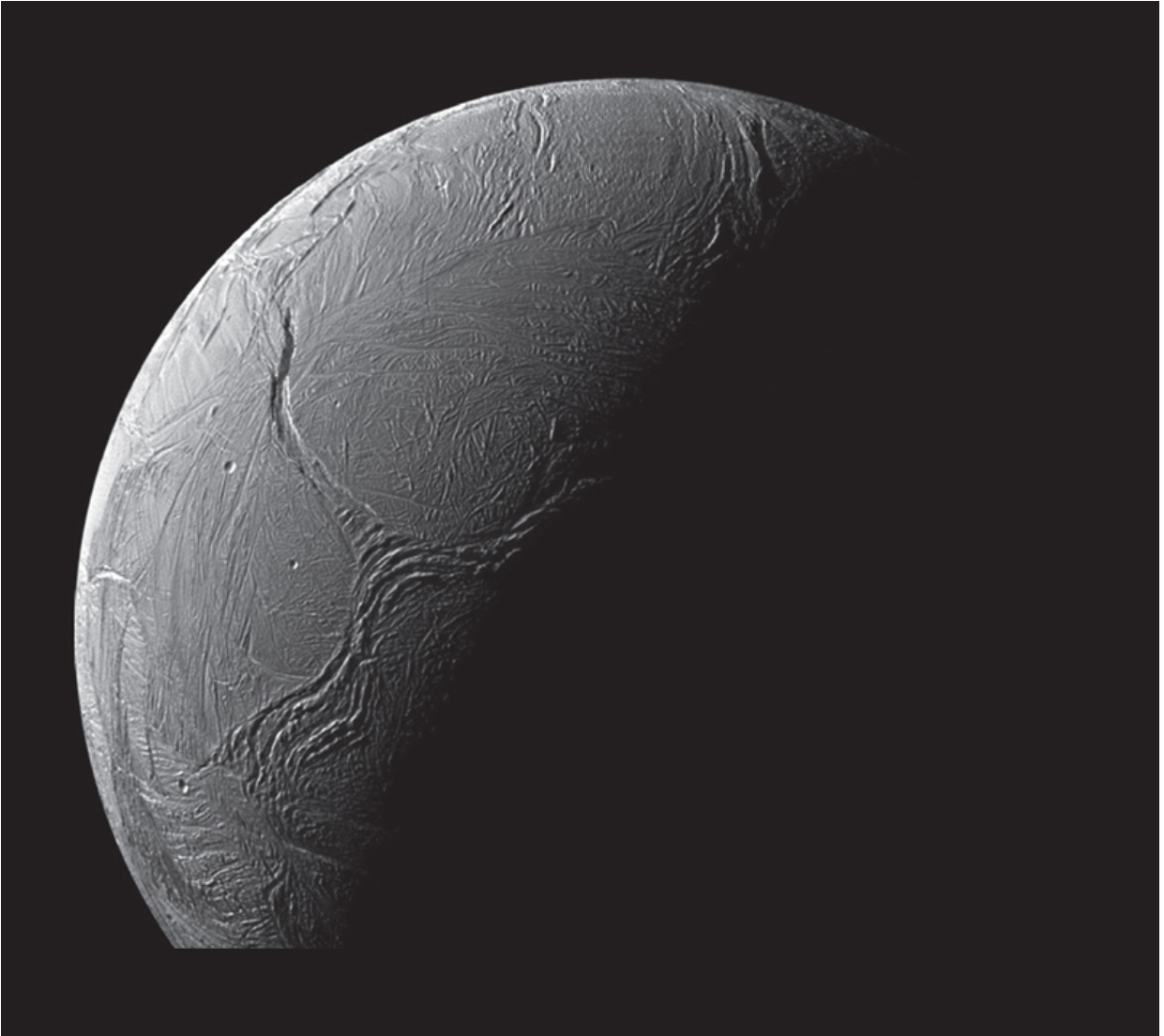
Long, linear cracks and ridges crisscross the surface of Jupiter's icy moon, Europa.



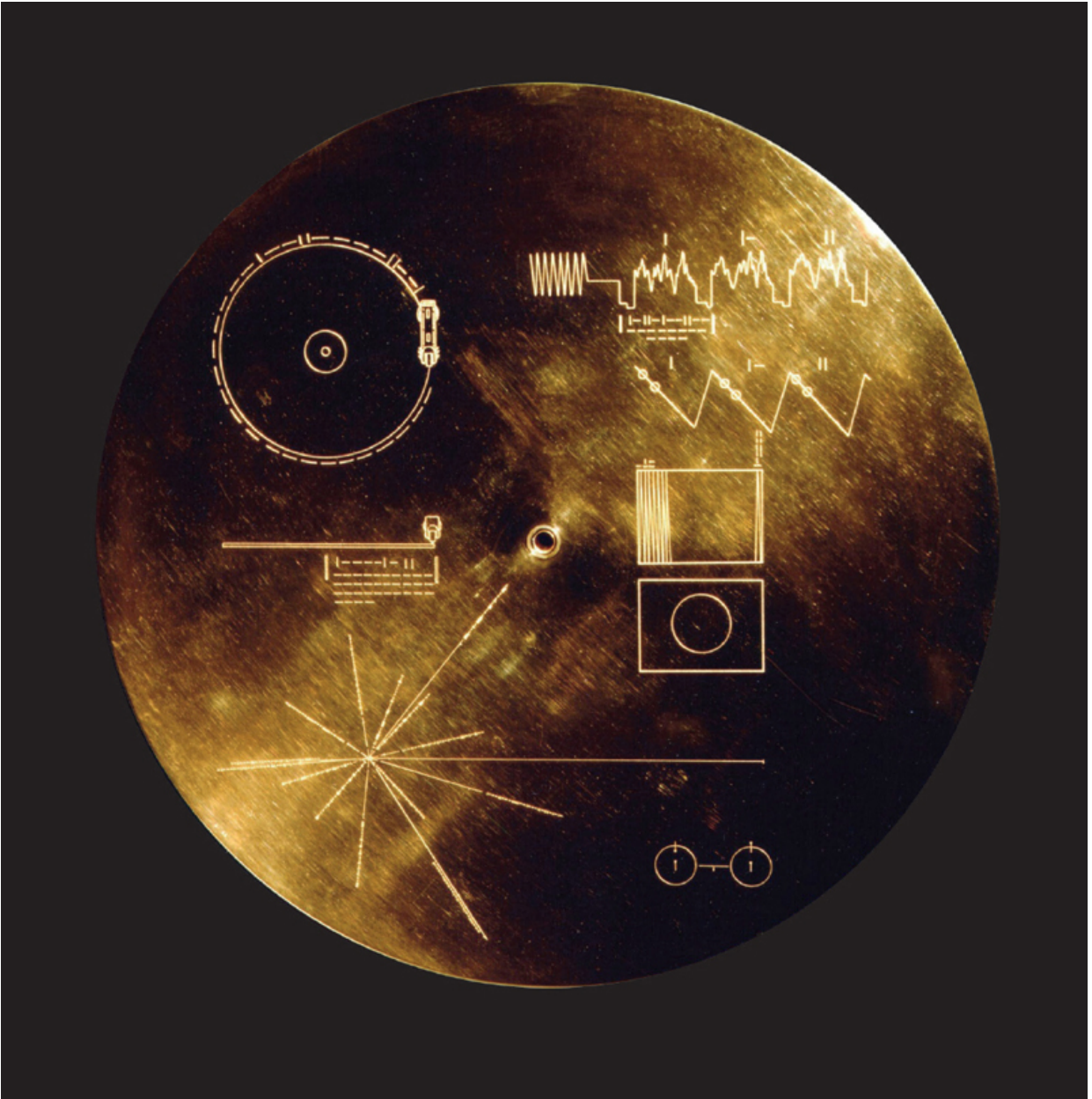
Jupiter's turbulent atmosphere is streaked with bands containing different gases as well as swirling storms, including its iconic Great Red Spot.



Saturn and its vast rings, as viewed from the Cassini spacecraft.



The surface of Enceladus, Saturn's satellite, seen by the Cassini probe. Jets of water vapour emanate from some of these cracks.

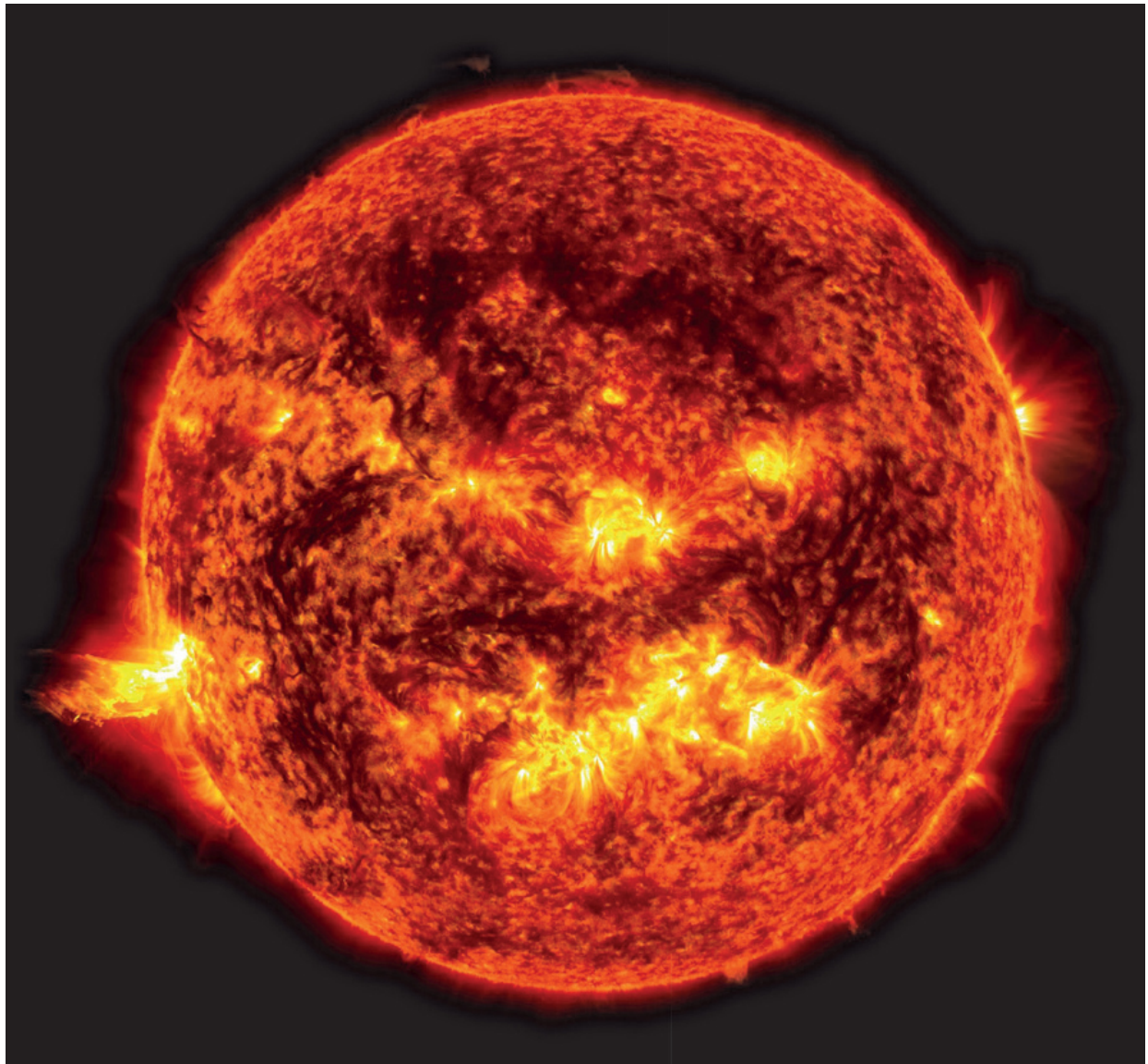


A golden record containing songs, images and sounds from Earth adorns NASA's Voyager spacecraft.



Edwin Hubble looks through the eyepiece of the 100-inch telescope at Mount Wilson in California. Hubble used this telescope to discover that the Universe is

expanding.



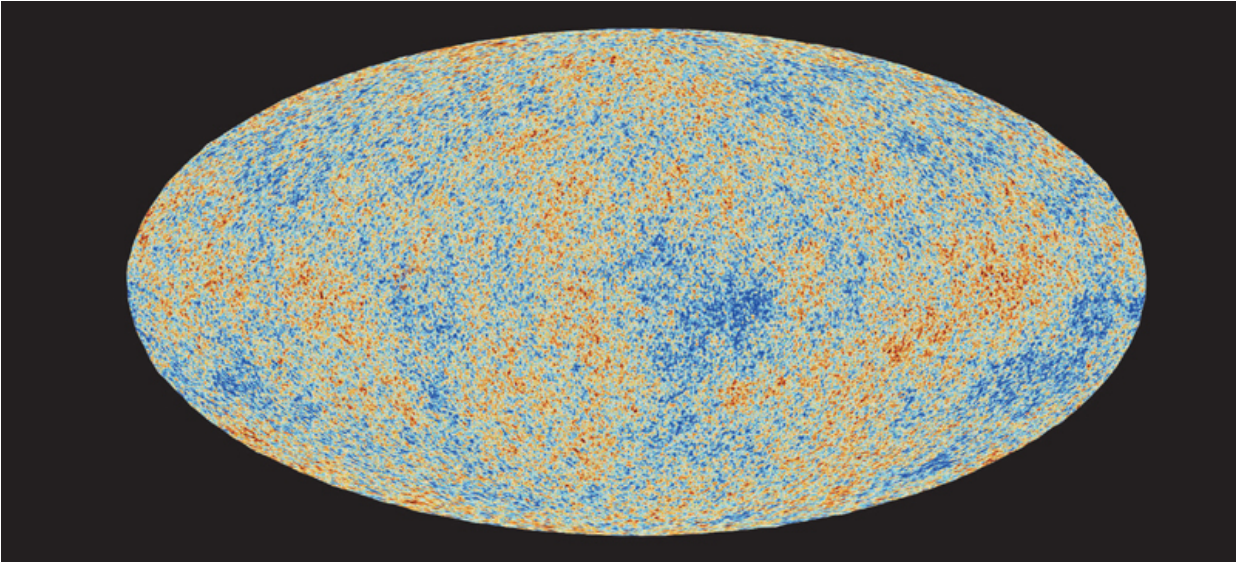
Vast flares and arcs of hot gas erupt from the scorching surface of the Sun.



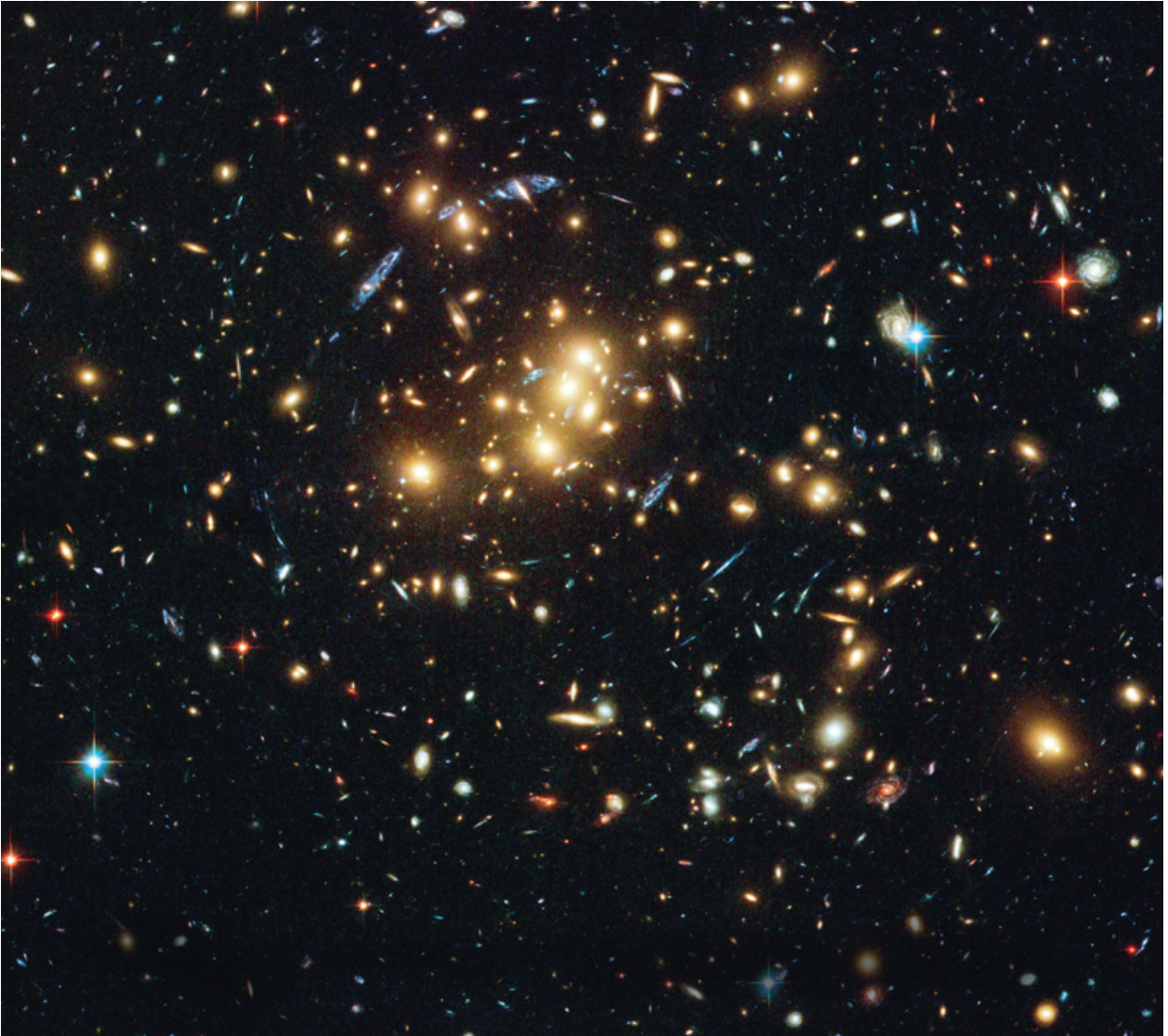
The Milky Way hosts hundreds of billions of stars as well as dark clouds that obscure our view.



The 'active' galaxy Centaurus A ejects jets of fast-moving particles from a black hole at its core (montage of observations taken across the electromagnetic spectrum).



The cosmic microwave background radiation, as measured by the Planck satellite. Each hot and cold patch marks over- and under-dense regions in the early Universe.



Galaxies and unseen dark matter in a foreground cluster distort background objects into arcs in a phenomenon known as 'gravitational lensing'.



Jets of particles shooting off the Sun, made visible during a total eclipse.

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